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Proceedings

NAVY/NASA VSTOL FLYING QUALITIES

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Edited by:

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FOREWORD

The Navy/NASA V/STOL Flying Qualities Workshop, which was held at the Naval Postgraduate School during 26 to 28 April 1977, had as its principle goal an information exchange by technical specialists working in the fields of flying qualities, stability and control, flight controls and displays and the ship interface area. The purpose of the workshop was the identification of problems and issues crucial for providing V/STOL flying qualities requirements applicable to future commercial and military aircraft.

The proceedings of the workshop are defined in the same manner as the actual workshop with separate sections presenting material covered in the sessions on flying qualities specification, aircraft development and flight testing, flight controls and displays, seaborne launch and recovery interface influences and workshop panel reports on the first, third and fourth areas. The comments made following each of the technical presentations are included in order to provide a record of the actual opinions and concerns of the various participants.

For reasons that are obvious, the workshop deliberately avoided placing concentrated attention upon any specific mission oriented V/STOL vehicle and attempted instead to maintain a broad viewpoint. However, the experiences associated with the AV-8A Harrier and the VAK-191B programs (which relate to specific vehicles) were reviewed from the standpoint of lessons learned in flying qualities requirements. It was the hope of the Workshop Committee that the underlying concern of identifying future flying qualities requirements would be the unifying thought running throughout the meeting. Because of the obvious Navy and Marine operational enviornments, the session dealing with the seaborne launch and recovery interface provided a valuable opportunity to alert the V/STOL technical community of the many difficult problems still remaining for solution when addressing all-weather shipboard operations.

Finally, lest we forget, the unofficial logo of the meeting probably was the oft repeated chart making the tradeoff comparison between display sophistication and stability augmentation complexity for comparable pilot workload task ratings. In spite of a humorous reaction during the meeting because of frequent reference to the chart (in several varied forms), we should not overlook the principle that all-weather operation of the V/STOL type aircraft cannot involve flying qualities requirements without also paying attention to the information implications to the pilot of display technology combined with the level of stability augmentation.

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The Workshop Committee extends a sincere thanks to the many participants, including our friends from the United Kingdom and Canada, who contributed by individual efforts to making the meeting productive. The editors of the proceedings would also like to state their appreciation to Mmes. Evelyn Basham and Lyn Logan from the Department of Aeronautics at the Naval Postgraduate School for their patience in transcribing tape records and assembling the written material.

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SESSION I

A COMPARISON OF V/STOL HANDLING REQUIREMENTS WITH THE VAK-191B

Seth B. Anderson
NASA Ames Research Center

1. Introduction

The rationale for the comparison was to examine the two available V/STOL criteria references: namely, AGARD 577 (principal guide for the VAK-191B flight test work) and MIL SPEC 83300 to compare them with flight measurements obtained on the VAK-191B along with the pilot's comments relative to the aircraft meeting the specifications, and also to see what differences there might be in the specifications themselves.

The main purpose, as noted in Figure 1, is to clarify some of the requirements for shipboard operation. Although there is some background of information for normal operation of V/STOL aircraft, there is not much experience to reflect upon handling qualities requirements to make an aircraft suitable for shipboard operation. A secondary purpose was to see how good the VAK-191 handling qualities were relative to the existing requirements. Finally, it is of interest to identify gaps in the current handling qualities documents.

2. Results and Discussion

In listing the V/STOL handling qualities, the format of AGARD Report 577 will be used, with the characteristics of control systems being the first topic for discussion (Figure 2). Here note that for the item of control force gradients, values are given from 577, from 83300, from tests of the VAK-191, and the pilot comments relative to the aircraft behavior and points in the criteria.

This particular area, the mechanical characteristics of the control system, has not been properly emplasized in the development of V/STOL aircraft over the years. In looking back at the various aircraft tested, in general, the control system characteristics have not met the specifications. The control force gradients shown by the specs indicate that for pitch we're looking for something between 1 to 3 pounds per inch of stick displacement. The VAK-191B values fell within the ballpark for both pitch and roll; however, a little high in yaw. As noted by the pilots' comments, one finds that even though the VAK-191 values are in the middle, the gradient is considered to be too large. The reasoning is that with the attitude command system, the pilot had to hold a sitck displacement to get a bank or pitch angle. When holding the force, the pilot tends to lose his precision of control -- enough to complain about it.

Another area that becomes more important with an attitude command system is good control harmony. This is one area where numbers were furnished in AGARD Report 577 and not in 83300. Definitely, more work is needed, particularly for the higher-order control systems to find out what harmony is really needed.

Moving on to the next area, Figure 3, Height Control Systems. This is, in my opinion, a very important area -- especially for shipboard

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operations. It's an area needing additional information to refine the requirements. As discussed in AGARD Report 577, the pilot wants the height control to remain fixed, which it didn't on the VAK-191. With the throttle arrangement on the VAK-191, the friction could not be adjusted by the pilot. If it were set correctly for cruise, the friction would be too high for hover when the pilot wanted to make fine adjustments.

The other part of Figure 3 lists criteria for powered control systems. Both specs require any oscillations to be well damped, and not cause pilot-induced oscillations (PIO). The lateral control system on the VAK-191 lacked viscous damping and contributed to lateral PIO in hover and low-speed flight.

Next item for discussion is pitch control power (shown on Figure 4.) We are concerned with how much control power is needed because of performance losses. For pitch control power, the criteria in AGARD Report 577 are given in terms of angular acceleration (radians per seconds squared) and pitch attitude change after one second. In examining the values for the VAK-191, pitch control power meets the AGARD 577 criteria guideline and also the 3 degrees after one second required in 83300, which includes trim. The total control power is judged to be adequate by the pilot.

One area for which there was no criteria is maximum pitch attitude. With the attitude command system $\pm$15 degrees was nominally available for full stick displacement. As noted in the pilots' comments, that wasn't quite enough nose-up angle for quick stops (deceleration). The item that really bothered the pilots was the low-pitch sensitivity. Control in pitch was obtained by bleed air and lift-engine thrust modulation. When using bleed air alone, the response was very low. As the control was moved farther on to the thrust modulation range, a nonlinear reqponse occurred.

The next area is longitudinal control in take-off (Figure 5); that is, the ability to rotate the aircraft to the take-off attitude. In the VAK-191 lift-off is achieved by changing thrust vector angle, and the criteria really are not adequate. Because of the bicycle gear arrangement, the pilot was concerned about over-rotating as the ground reaction moment decreased to zero at lift-off. Both of the criteria guard against this undesirable response. Two other areas of concern include complicated control manipulation for take-off and the ability to check for proper control functioning before lift-off. Both these items were trouble spots in the VAK-191.

Next is the roll axis (Figure 6). Control power requirements are stated in the same way as for pitch. The VAK-191B had about 1.4 radians per second squared in roll, and 13 degrees after one second. That wasn't enough bank angle available for turning in a 60-knot STOL approach (the pilot wanted more than 15^{o} bank angle). Roll control power was adequate only for no-wind conditions, and the cross-coupling (dihedral effect) required control power to trim.

Linearity of response was also a problem with the VAK-191. When the pilot displaced the stick to make a lateral sidestep maneuver, the SAS provided trim for the rolling moment due side velocity. When the stick was returned to neutral, there was a tendency to overshoot bank angle, resulting in a PIO tendency. The last item noted on Figure 6 is the fact that the SAS could exert 100% control authority for trim for aircraft that

have large rolling moments due to sideslip. An important consideration is to establish a realistic margin for maneuvering. We don't have a good answer on that. Mil Spec 83300 covers this by requiring a 50% margin which is very arbitrary and may penalize certain types of aircraft.

Shown next on Figure 7 is cross-coupling. It has been mentioned that positive dihedral effect is large on the VAK-191B aircraft. At 100 knots and 5 degrees angle of attack, the pilot is limited to 5 degrees of sideslip angle. At 60 knots the roll trim capability is limited to about 10 degrees of sideslip, which is not a lot of cross-wind capability. The Harrier has the same basic problem. The criteria covers this point adequately except for the fact that the 50% margin is certainly not a final answer. In addition, the pilot needs a warning of how much margin is available for maneuvering.

Next consider vertical flight path characteristics (Figure 8). The first item is ground effect. Mil Spec 83300 does not cover ground effect items. As noted by the pilots' comments, positive ground effect caused a small problem because it made the aircraft more difficult to control close to the ground. This is an area that deserves further attention to define what the pilot wants in quantitative terms.

The next area listed (Figure 9) is vertical thrust margins. Sufficient margins are needed to get out of ground effect quickly, particularly with jet-type aircraft. For example, the VAK-191 was adequate with a margin of 1.1, but if the pilot stayed in ground effect very long, the margin decreased to 1.05 because of convection heating of the air. Another subject for discussion is thrust response which raises the point about split throttle operation. For height control the pilot can use either the main engine thrust lever or the lift-engine thrust lever, or a combination of both. The first-order time constant was about 0.58 second which didn't meet either specification. The pilot didn't complain about this low value although this would be much more of a problem for shipboard operation.

The first item in transition characteristics (Figure 10) is Acceleration/Deceleration. AGARD Report 577 states that a value of at leaast 0.5 g be available in level flight. The VAK-191 has a reasonable value initially (approximately 0.5 g) because one-half of the thrust can be vectored forward. At about 200 knots, however, acceleration drops off markedly because of the large ram drag built up on the main engine and the large induced drag characteristic of low-aspect-ratio wing. Further work (and operational experience) is needed to define acceleration requirements more quantitatively.

Going in the other direction, the aircraft can slow down quite rapidly from an approach speed of 200 knots. Again, more accurate deceleration values are needed, particularly for shipboard operation where a display will be needed to help the pilot make some kind of a judgment of how well the optimum deceleration schedule is going.

In summary (Figure 11) the following points are make:
The current handling qualities requirements certain need refinement for shipboard operation. At the time the handling qualities requirements were written (1970), shipboard operation was not seriously considered. As noted, control power, height control, and thrust response are primary areas needing refinement.

The VAK-191 handling characteristics did not meet the existing handling qualities requirements in certain critical areas. This included total control power about all axes, control sensitivity, and control linearity, ground effect, height control, and cross coupling.

The two handling qualities documents are in general agreement, but certainly lack coverage in key areas.

P U R P O S E O F P R E S E N T A T I O N

- CLARIFY HANDLING QUALITIES REQUIREMENTS FOR SHIPBOARD OPERATION
- COMPARE VAK-191B HANDLING QUALITIES WITH EXISTING HANDLING QUALITIES REQUIREMENTS
- IDENTIFY GAPS IN HANDLING QUALITIES REQUIREMENTS

Figure 1

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HANDLING QUALITIES COMPARISON

CHARACTERISTICS OF CONTROL SYSTEMS

ITEM	AGARD RPT NO.577	MIL. SPEC. 83,300	VAK-191B	PILOT COMMENTS
CONTROL FORCE GRADIENTS lb./in.	The force gradient shall not be less than the break out force Pitch 1-3 lb.	0.5 - 3	2.2	Prefer pitch force gradient to be reduced for attitude command control system because of need to hold control force to command pitch attitude.
	Roll 0.5 - 1.75 lb.	0.5 - 2.5	2.1	Combined effects of high breakout forces and gradient result in poor feel and centering about trim - could contribute to lateral PIO tendencies noted in flight.
	Yaw 2.5 - 10	5 - 10	13.5	High breakout and force gradient [illegible] make accurate control of sideslip difficult when combined with sluggish aircraft response in yaw, in hover and high yaw sensitivity at 60 kts.
CONTROL FORCE HARMONY RATIO	Optimum Pitch/Roll, 2	No values stated (response shall be harmonious)	Pitch/Roll, 1	Good harmony important for attitude command control systems. Pitch/roll ratio should be 1 if forces are light, 2 if forces are heavier.
	Yaw/Roll, 6		Yaw/Roll, 6.4	

Figure 2

HANDLING QUALITIES COMPARISON

CHARACTERISTICS OF CONTROL SYSTEM

ITEM	AGARD RPT NO.577	MIL. SPEC. 83,300	VAK-191B	PILOT COMMENTS
HEIGHT CONTROL SYSTEMS	Height control should remain fixed unless moved by pilot or some automatic system.		Height control (lift engine throttles) can move against the pilots hand to provide attitude stabilization.	The uncommanded movement of the height controls caused by the pitch control system (thrust modulation feedback) was considered unsatisfactory.
	An adjustable friction device is desirable.		No friction adjustment provided.	Lack of friction level control unsatisfactory because control can move inadvertantly when hand is removed to adjust nozzle vector angle.
POWERED CONTROL SYSTEMS	Control systems oscillations should not adversely affect precision of control, or cause pilot-induced oscillation.	All control systems oscillations shall be well damped.	Lateral control system lacks viscous damping.	Lateral PIO can occur if stick is released - lack of control system damping is unsatisfactory.
	Failure of powered-control system should not restrict operational maneuvers required for the mission		Failure of powered control system would result in reversion to mechanical linkage system.	Mechanical backup system not suitable for hover due to large breakout forces, friction, backlash and force gradients.

Figure 3

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HANDLING QUALITIES COMPARISON

LONGITUDINAL STABILITY AND CONTROL

ITEM	AGARD RPT NO.577	MIL. SPEC. 83,300	VAK-191B	PILOT COMMENTS
PITCH CONTROL POWER	0.4 to 0.8 rad/sec^2	$\pm$ 3.0 degrees attitude change after one second (wind from most critical direction).	1.0 rad/sec^2 8.0 deg after 1 sec $^{+}_{-15^o}$ pitch attitude available	Total control power is adequate but response was lower than desired in the thrust modulation deadband. Need 20^o nose-up and 15^o nose-down attitude.
PITCH CONTROL SENSITIVITY	3-5 deg/in	3-20 deg/in	3.5 deg/in	Pitch response is sluggish for small inputs.
LINEARITY (a/c response to control input)	Constant or not abruptly increase nor change sign.	There shall be no objectionable non-linearities.	Nonlinear in going from bleed air to thrust modulation. A/C oscillations of 0.5 cps for small control inputs	Small pitch control inputs within the differential thrust deadband resulted in oscillatory aircraft motion.

Figure 4

HANDLING QUALITIES COMPARISON

LONGITUDINAL STABILITY AND CONTROL

ITEM	AGARD RPT NO.577	MIL. SPEC. 83,300	VAK-191B	PILOT COMMENTS
LONGITUDINAL CONTROL CHARACTERISTICS IN TAKE-OFF	Control effectiveness should not restrict STOL operation; shall be sufficient to initiate rotation at the designated speed or at least 2.0 sec before lift-off; and adequate control margin and pitch rate damping shall exist to prevent rotation to undesirable attitudes. Control shall be sufficient to rotate in ground effect.	Elevator control shall not restrict take-off performance and shall be sufficient to prevent over-rotation to undesirable attitudes.	Pitch rotation obtained by lift engine thrust modulation.	Due to landing gear geometry, lift-off by rotation was accompanied by pitch overshoot requiring corrective pilot action. Due to control and stability augmentation system functions, feedback into the lift engine throttle and reduction in lift-engine thrust occurred. This feature is highly undesirable because LE throttle is unguarded.
		Satisfactory take-offs shall not be dependent upon complicated control manipulation. Control travel during take-off shall not exceed 75% of total travel.	Approximately 15 steps required in STO procedure. Lift engines are started during take-off run to minimize ground erosion and hot gas ingestion.	Due to high workload associated with lift engine start during the take-off roll, the PR is 7. If wheel brakes are released after LE are running and checked out, PR is 2.
	For all types of take-off operation, it is desirable to check for proper control functioning during run-up at less than take-off thrust.			The need to functionally check out lift-engine performance during engine run-up urgently exists.

Figure 5

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HANDLING QUALITIES COMPARISON

LATERAL-DIRECTIONAL STABILITY AND CONTROL

ITEM	AGARD RPT NO.577	MIL. SPEC. 83,300	VAK-191B	PILOT COMMENTS
ROLL CONTROL POWER	0.4-1.5 rad/sec^2	$\pm$ 4.0 degrees attitude change after one second.	1.4 rad/sec^2 13.4° after 1 sec for full δ_a $\pm$15° roll attitude available	Adequate for hover with no wind. Inadequate for full flight envelope maneuvering. Need more than $\pm$15° roll angle for STOL maneuvering
ROLL CONTROL SENSITIVITY	3-5 deg/in	4-20 deg/in	5.4 deg/in	Lateral response too sensitive in hover tending toward PIO.
LINEARITY	Constant or should not abruptly increase or change sign.	There shall be no objectionable nonlinearities in aircraft response.	Abrupt change in roll response when lateral control was returned to neutral in side step maneuvers.	Roll overshoot on recovery from sidestep maneuvers was objectionable and could lead to PIO.
			SAS can exert 100% control authority.	Loss of lateral control masked from pilot by capability of 100% authority SAS to create deadbands near full-stick deflection.

Figure 6

HANDLING QUALITIES COMPARISON

LATERAL-DIRECTIONAL STABILITY AND CONTROL

ITEM	AGARD RPT NO.577	MIL. SPEC. 83,300	VAK-191B	PILOT COMMENTS
CROSS COUPLING	At reference speed for STOL operation $\Delta\beta/\Delta\phi$ not to exceed 0.3 to 0.5 or 20° sideslip angle.	$\Delta\beta/\phi$, maximum change in sideslip angle to initial peak bank angle not to exceed 1.65.	$\Delta\beta/\Delta\phi$ is essentially zero in transition speed range	Satisfactory, little sideslip induced. In aileron only turns in speed range up to 120 knots.
DIHEDRAL EFFECT	Positive dihedral limited so that sufficient roll control remains to correct for gusts, upsets, and maneuvering.	Positive dihedral effect should never be so great that more than 50% roll control power needed for sidelip excursions.	At 100kt and 5° angle of attack, β limited to 5°. At 50kt, α = 10°, β limited to 10°.	Operational crosswind envelope of 10kts unsatisfactory. No warning of sideslip limits, unacceptable for operational use

Figure 7

HANDLING QUALITIES COMPARISON

VERTICAL FLIGHT CHARACTERISTICS

ITEM	AGARD RPT NO.577	MIL. SPEC. 83,300	VAK-191B	PILOT COMMENTS
GROUND EFFECT	Downwash/ground interference should not result in unsatisfactory characteristics during hover and STOL operations.		Positive ground effect evident in no wind, stationary hover. Maneuvering or tail wind conditions could result in recirculation in rear lift engine.	Height control difficult due to non-linear response associated with positive ground effect, recirculation (exhaust ingestion) in rear lift engine resulting in pitch attitude changes, and consequent reduction in height control power.
	Following failure of a power control system or SAS, it should be possible to make a safe landing.		Reversion to manual control system increases control system friction to large values.	Loss of either powered control or SAS would make safe landing questionable.

Figure 8

HANDLING QUALITIES COMPARISON

VERTICAL FLIGHT CHARACTERISTICS

ITEM	AGARD RPT NO.577	MIL. SPEC. 83,300	VAK-191B	PILOT COMMENTS
VERTICAL THRUST MARGINS	Maximum thrust-to-weight ratio. T/W, available at the most critical value of vertical velocity damping shall be: Take-off: 1.05 and not less than 600fpm climb rate Landing: 1.03-1.10	Steady state thrust-to-weight ratio available T/W, shall not be less than: 1.05	Height control obtained by combined thrust of lift and cruise engines. T/W available can go from 1.1 down to 1.0 in ground effect.	Height control with matched throttle (lift/main engines) was satisfactory when T/W was 1.0; inadequate when reduced to 1.05. Height control with split throttle resulted in speed/altitude coupling due to reduced throt sensitivity, exhaust geometry, and asymmetric lift engine response resulting in unacceptable height contr
VERTICAL VELOCITY AND THRUST RESPONSE	Normal acceleration, g/in should be in the range 0.1 to 0.4.		Split throttle operation resulted in a sensitivity of .04 g/in.	Low sensitivity resulted in excessive height control lags. Desire approximately .075 g/in per throttle.
			Front lift engine has faster thrust response.	This caused problems in lift-off dynamics, linearity of longitudinal control and height control.
	First-order time constant should not be greater than 0.5 sec.	Achieve 63% of commanded incremental thrust in not more than 0.3 sec.	Time constant of combined throttle response = .85 sec	Lift engine thrust response considered good - cruise engine response was inadequate and led to overcontrol tendencies.
			Automatic limiting of maximum power is incorporated resulting in a region on throttle deadband.	Pilot should be warned of approaching deadband operation and a thrust margin of approximately 10% should be provide
				Deadband resulted in excessive degradation of ehight control due to nonlinearity and reduced sensitivity.

Figure 9

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HANDLING QUALITIES COMPARISON

TRANSITION CHARACTERISTICS

ITEM	AGARD RPT NO.577	MIL. SPEC. 83,300	VAK-191B	PILOT COMMENTS
ACCELERATION/ DECELERATION	Acceleration and deceleration values up to 0.5g in level flight are desired.	It should be possible to accelerate rapidly and safely to V_{con} and decelerate rapidly and safely. Time taken for these maneuvers to be designated by mission requirements.	Maximum deceleration limited to .25g.	Need no more than 0.15 to 0.18 g capability deceleration for night or IFR operation.
	It should be possible to accelerate continously from a rolling take-off to V_{CON} and vice-versa.		Acceleration capability reduced from a maximum of g at take-off to 0 g at 200 KTS.	Acceleration inadequate in upper transition speed range. Transition mode required constant pitch trim to prevent pitch up during acceleration.
			Trim pitch force change =	Trim requirements should be minimized transition due to high pilot workload.
FLEXIBILITY OF OPERATION	Direction of transition should be easily reversible.	It should be possible to stop and reverse the transition quickly and safely.	Transition performed by positioning cruise engine nozzle.	Transition could be stopped or reverse at any time.
	Failure of a single engine, SAS, or power control system shall still allow a safe landing on wave-off.		A lift engine failure would require a conventional landing	Conventional larding would be extremel dangerous because of poor flight path control and field length requirements.
TOLERANCE IN CONVERSION	Changing from hovering to conventional flight and vice-versa should be low pilot workload.	It should be possible to change from hover to V_{con} and vice versa without excessive pilot skill and attention.	Conversion requires complex lift engine operation, large attitude change and close airspeed control.	Conversion sequence too complex and pilot workl d too high for operationa use.

Figure 10

CONCLUDING REMARKS

- CURRENT HANDLING QUALITIES REQUIREMENTS NEED REFINEMENT FOR SHIPBOARD OPERATION
- VAK-191B AIRCRAFT DID NOT MEET EXISTING HANDLING QUALITIES REQUIREMENTS IN CRITICAL AREAS
- CURRENT HANDLING QUALITIES DOCUMENTS WERE IN GENERAL AGREEMENT, BUT LACK COVERAGE IN SEVERAL AREAS

Figure 11

DISCUSSION

Andie Byrnes: Could you make any remarks on the factors influencing the selection of pitch attitude command angles, and what were the reasons for the pilot desiring those angles?

Seth Anderson: For this question, let me ask a pilot to respond. Lt. Col. Iles who flew the VAK-191 aircraft in Germany is in the audience. Bud, would you care to remark on the considerations that went into establishing the pitch attitude angles?

Lt. Col. J. E. Iles, USMC: The attitude problem came about because we couldn't obtain the required response for making precise position corrections such as when approaching or positioning to a spot. This would be particularly important if the situation corresponded to having a moving deck, or if it were at night when your perception of the external positioning cues were degraded. The attitude limitations contribute to that problem. The other reason for needing more nose-up attitude was that in order to generate the longitudinal decelerations to meet the requirement to decelerate from approximately 60 knots in 1/4 mile, I needed slightly more nose-up pitch attitude change to generate that longitudinal deceleration. I thought a good operational goal to achieve was the abiliity to decelerate the aircraft through an attitude change alone in a 1/4 mile from 60 knots.

Trevor Wilcock: In Harrier operation, the close-in deceleration can be made by thrust nozzle operation; hence, the attitude changes are not required.

Lt. Col. Iles: The VAK-191 was limited for developing deceleration by nozzle deflections; hence, a 20-degree nose-high attitude was required. From a combat maneuvering standpoint, you might want higher deceleration rates. My comments were oriented towards the night IFR approach where the 0.1 g deceleration close-in becomes uncomfortable due to degradation of visual cues.

Anderson: This is an area where display/guidance information is needed to assist the pilot in determining how well he is doing; then a larger deceleration could be tolerated. At present, deceleration is conducted open loop. The work at NASA/Langley Research Center on the CH-46 showed that 0.05 g's deceleration was all that the pilot could tolerate and still feel comfortable; hence, a display is a real requirement in establishing "how-goes-it" information.

Lt. Col. Iles: Remarks made for the Harrier relative to changing the thrust vector at constant attitude were correct. However, it is probably correct that deceleration by attitude changes will distort your visual cues and make things uncomfortable.

Dave Green: One other aspect not to lose track of is that high g VFR deceleration requirement allows one to keep both fuel usage and engine time down. Must bear in mind that an expense item is related to the "ilities".

Hal Fluk: Have you given any thought relative to providing an indication of the thrust-to-weight margin that is desirable for landing vertically on a deck that is experiencing large vertical, heaving, and pitching displacements?

Anderson: That is a good question, because I'm sure that we don't have the answers yet that we are seeking. One always desires as much margin as possible, and fortunately in landing, one has a bit more margin than in take-off. In my recollection, the criteria state that 1.1 is required for landing. The reason for this large value is to be able to check a high rate of sink close to the ground. In take-off, 1.05 allows ample margin to leave the ground with a modest rate of climb. Whether 1.1 is adequate for land-in a shipboard environment is uncertain. I would suspect that if 1.1 were the criteria for normal operations, one would expect the shipboard requirement to be higher.

Dave Green: You mentioned earlier some remarks relative to force gradient characteristics. I think that experience has shown in other machines that with attitude proportional control, a soft breakout with shallow force gradients, along with good, strong, viscous damping, will provide the characteristics that pilots desire for slow-speed maneuvering. That is something which has been discovered only about 15 years ago by helicopter people.

Anderson: We all agree with you. Thanks for the comment.

Sam Craig: I do not want to contradict Dave totally, but one has to be careful when using viscous damping in a system because of a restrictive influence to the pilot on bandwidth. It is possible to have a net result that is worse than without dampers. You cannot have a break-frequency of less than one hertz; otherwise, you are in trouble. So one should be careful when stating the use of viscous campers in an all-encompassing manner.

Dave Green: I agree.

Sam Craig: As an aside, one should recollect the comment on position control. Attitude control in the VAK-191 is an inner loop for position control, while the outer loop is a position command. Therefore, one cannot independently set up attitude requirements without considering the outer-loop control.

Anderson: Looking back at it now, one would say that the VAK-191 control system was not really the type that one would want. One would probably desire attitude hold, rate command, or possibly some other higher-order system. Although there are deficiencies in a proportional system (attitude command), it helps reduce pilot workload because if the pilot releases the stick, he knows that the aircraft will level off. Anything done to reduce the pilot workload in the VAK-191 was a step in the right direction due to the complexities in cockpit procedures.

MIL-F-83300; VIEW FROM AN AIRCRAFT DESIGNER

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ABSTRACT

The MIL-F-83300 V/STOL Flying Qualities Specification is reviewed from three aspects: a) its effectiveness as a guide to the attainment of well balanced V/STOL aircraft design, b) the relevance of its requirements to the successful emergence of the Harrier; and c) its relative merits and deficiencies when compared to the AGARD V/STOL Handling Criteria. Suggested changes for making it a more useful tool for the V/STOL Aircraft Designer are presented.

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1. Introduction

I would like to begin by pointing to the fact that, even though we have been working on the design of V/STOL flying machines for many years, we are still in the infant stage of the art. The term "art" rather than "science" is used deliberately. It is also considered necessary to warn you that my view is prejudiced strongly by my involvement over the last six years with the specific concept of V/STOL used in the Harrier, i.e. vectored thrust.

When asked by our Chairman to write a paper on the V/STOL flying qualities specification, the first question which came to mind was: "What should a good specification do?" Reviewing my 27 years of design experience on military fighter-attack aircraft, I came up with the following answer. A good flying qualities specification should serve two ends:

- It should provide guidance to aircraft designers toward effecting good flying qualities and flight safety in their designs.

- It should provide a practical base on which the customer and manufacturer can define a specific aircraft.

Within this frame of reference, I believe that MIL-F-83300 is a good start, but that many improvements should be made, both in its specific requirements and in its general approach toward these ends.

2. Specification Philosophy

When considering the philosophy, or general approach to a specification, a bit of sage advice from a fine professor of years gone by came to mind. He conveyed the idea rather graphically in a little cartoon which was included in his book titled "Aircraft Design" (see Figure 1).

My view is that like the cartoon implies we often take our specifications a bit too seriously; often times more seriously than the author or group of people who put the specification together in the first place. In my view, this syndrome has and still does tend to work to the detriment of good well-balanced aircraft configurations. For instance, I see a strong tendency to oversize V/STOL aircraft because Paragraph 3.2.5.1 in the Specification implies that the incremental vertical acceleration capability must be at least 0.1g under the worst possible combination of conditions such as with the rolling acceleration or yawing acceleration capability maintained above certain prescribed values under the worst combination of store loadings, ambient temperature, crosswind and gross weight. Gentlemen, I don't believe that we can yet afford such luxuries in V/STOL aircraft. Every successful aircraft system I have ever been associated with has evolved from a series of hard fought and often agonizing compromises.

Let's look at the relevancy of the vertical acceleration requirement in the light of actual flight experience on the Harrier. An average vertical acceleration from lift-off to 20 ft of height as low as .0125 g is still considered an acceptable VTO. An average acceleration of .050g is termed a "Good-Go" i.e., one with which the pilot is very comfortable. Actually there is a good deal of evidence which suggests that vertical accelerations in excess of this value can actually be very dangerous in the event that an unrecognized lateral weight asymmetry is present at lift-off. Such asymmetries have occurred in the Harrier experience as

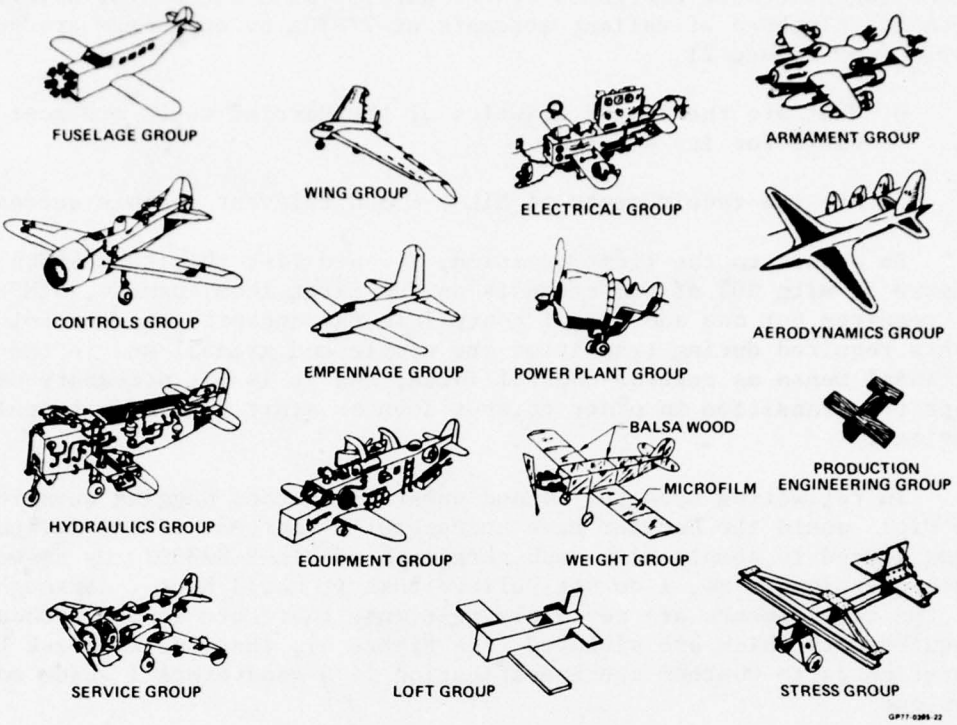


FIGURE 1
DREAM AIRPLANES

the result of faulty fuel transfers from one side of the aircraft. Almost all, if not all, of the reported incidents involving excessive roll during VTO's have occurred at relatively low gross weights wherein the vertical acceleration was rather high. Somewhat contrary to the Specification requirements, then, the preponderence of VTO flight experience would suggest that, in the interests of flight safety, an upper limit be placed on the vertical acceleration experienced during VTO's and that a lowering of the minimum target vertical acceleration is at least acceptable and perhaps desireable.

With the aerodynamic-propulsion interactions being so predominant in V/STOL machines, and the nature of the various concepts so radically different from one another, I believe it is unwise to be overly specific in the requirements; especially when, as is the case with MIL-F-83300, the flight experience has been predominantly with helicopters in the low speed mode of operation and wing-borne aircraft in the high speed region of transition. I think we would be wiser to lean more in the direction taken by the AGARD Committee and present design criteria in many areas, as opposed to hard-line quantitative requirements not thoroughly supported by flight data on V/STOL aircraft.

Perhaps this may be considered a radical departure, particularly for those of you representing procurement agencies. It is my conviction, however, that such changes in our approach are indeed necessary if the United States is to lead the world in V/STOL Aviation. I hope that the following paragraphs will lend some credence to this contention.

Many times during the last five years, I have asked myself two questions regarding the emergence of the Harrier as a successful aircraft from the plethora of valiant attempts at V/STOL by engineers around the world (see Figure 2).

- What are the characteristics of the Harrier which are most responsible for its success?

- Are the requirements of MIL-F-83300 relevant to this success?

In answer to the first question, I would list the items shown in Figure 3, with 80% of the emphasis on the first item, namely, SIMPLICITY. It requires but one additional control in the cockpit; the control movements required during transition are simple and gradual and in the traditional sense as regards control force, and it is not necessary to interrupt the transition in order to shut down or start auxiliary propulsion devices.

In reflecting upon the second question another nagging question arises, to wit: would the Harrier have successfully emerged had its designers been forced to comply with each paragraph of MIL-F-83300? My answer to this question is no, I do not believe that it would have. Although many of the requirements are certainly relevant, there are so many fundamental requirements which are violated (see Figure 4), that one must ask the question as to whether the Specification is a good overall guide to the designer.

Would the Harrier be a better aircraft if it met more of the Specification requirements? In some areas, meeting more of the requirements would be an improvement; in others, I believe compliance would have negligible, if not a detrimental effect. Are any of the improvements achievable with today's technology and economic environment? Again, my answer would be yes in some cases; no in others.

First of all, let's reflect a moment on what the characteristics of a successful aircraft are.

- It must meet the primary needs of a customer
- It must be cost effective
- It must have a long production life

Obviously, all three of these characteristics are interdependent. They are separated herein in order to emphasize the need for us to consider these aspects when laying down specifications which must be complied with in the real world. The authors of a specification may be realistic about the limitations of their creation, but once it gets down on paper and published, it often takes on an aura of validity far and beyond the data on which it is based.

I would like to belabor you with one more fundamental point before getting into the discussion of particular paragraphs and recommended changes. As illustrated in Figure 5, there are many considerations and tradeoffs which must be made in a well-balanced aircraft design, not the least of which are reliability, maintainability, cost and schedule. If a flying qualities specification is to fulfill its function, it must be somewhat amenable to these factors.

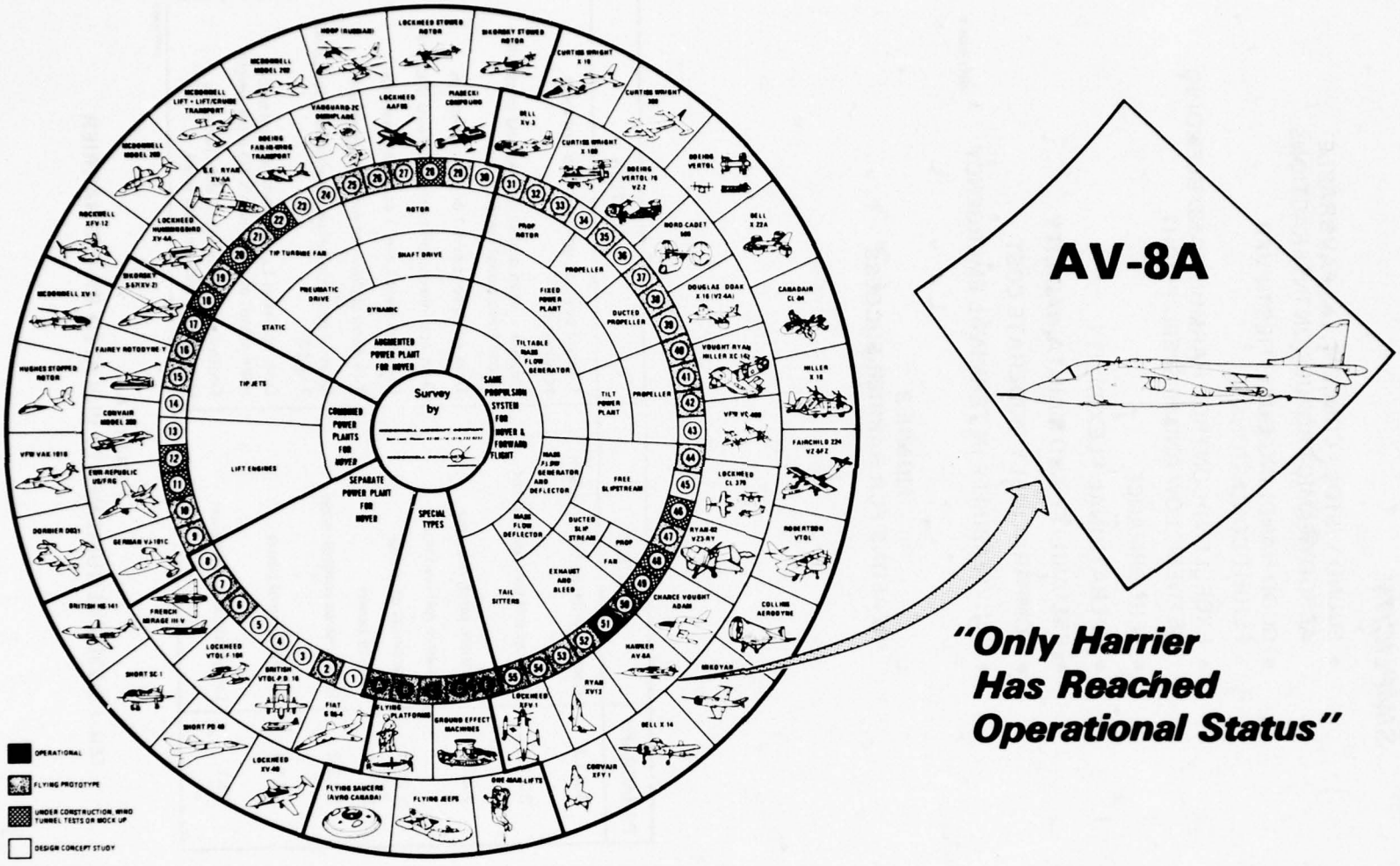


FIGURE 2
V/STOL RESEARCH AND DEVELOPMENT

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SIMPLICITY

- SOUND V/STOL - CONCEPT, i.e., FAVORABLE AERODYNAMIC-PROPULSION INTERACTIONS
- GOOD HANDLING QUALITIES IN VFR FLIGHT CONDITIONS
- EXCELLENT CONTROL HARMONY AND BLENDING BETWEEN LOW AND HI-SPEED FLIGHT
- PERFORMANCE
- OPERATIONAL FLEXIBILITY
- RELIABILITY AND MAINTAINABILITY
- COMPARATIVELY MODERATE COST
- SURVIVABILITY IN TERMINAL EMERGENCY

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FIGURE 3
REASONS FOR HARRIER SUCCESS

PARAGRAPH	SUBJECT	VIOLATION
3.2.1.3	Cockpit pitch control gradient	Control position gradient does not meet requirements
3.2.1.3	Cockpit roll control gradient	Reverse aileron deflection required to stabilize lateral transitional velocity
3.2.2.1	Dynamic pitch response	Does not meet Level 1 or 2 requirements
	Dynamic roll response	Does not meet stability requirements SAS off
3.2.2.2	Directional damping	Does not meet Level 1 or 2 requirements
3.2.3.1	Control power	Yaw control does not meet requirement
3.2.3.2	Response to control input	Control response below requirements for Levels 1 and 2
3.2.5.1	Height control power	Does not meet Level 1 vertical acceleration requirement at maximum VTO gross weight
3.3.1	Longitudinal Equilibrium	Control position gradient does not meet requirement with nozzles fixed

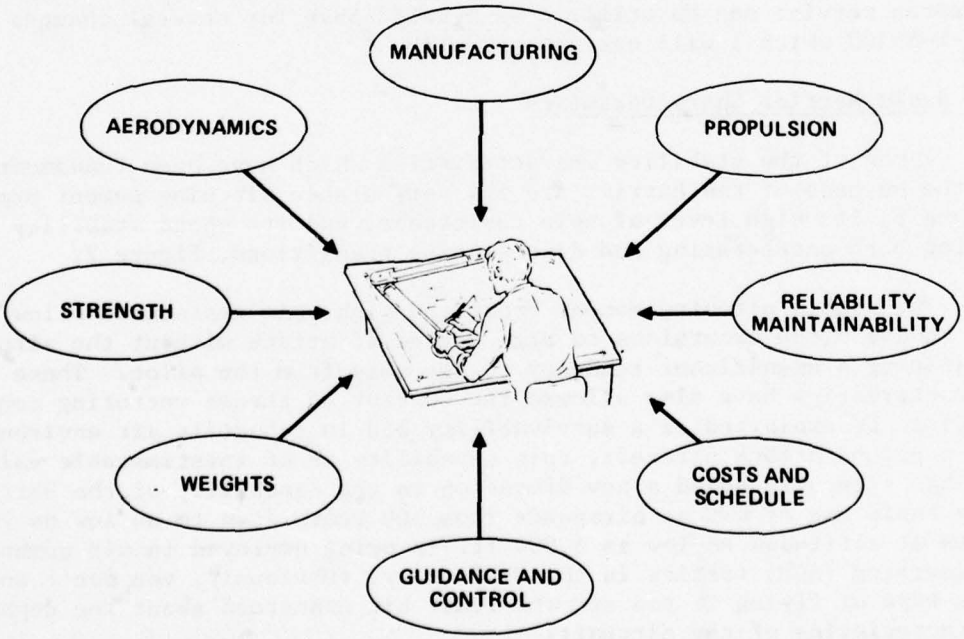
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FIGURE 4a
MIL-F-83300 REQUIREMENTS VIOLATED BY THE HARRIER

PARAGRAPH	SUBJECT	VIOLATION
3.3.2	Longitudinal dynamic response	Does not meet stability or time to double amplitude requirements
3.3.4	Pitch control feel and stability in maneuvering flight	Does not meet control position gradient with α with nozzles fixed
3.3.7.1	Lateral-directional oscillation (Dutch roll)	Aircraft does not meet Levels 1, 2 or 3 requirements SAS off
3.3.8.1	Bank angle oscillations	Does not meet Level 1 requirements
3.3.8.2	Sideslip excursions	Does not meet Level 1 requirements
3.3.9.1	Roll control forces	Roll force is below minimum for Levels 1 and 2
3.3.10.1	Directional response to yaw control input	Directional response below Level 1 requirement
3.3.11.1	Yawing moments in steady sideslip	Control force and deflection are in unstable sense
3.5.1.1	Control centering and breakout forces	Maximum allowables exceeded

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FIGURE 4b
MIL-F-83300 REQUIREMENTS VIOLATED BY THE HARRIER (CONTINUED)



GP77-0395-7

FIGURE 5
AIRFRAME DESIGN CONSIDERATIONS

3. Suggested Changes in Philosophy

I would be the last to suggest that MIL-F-83300 should compromise good flying qualities and flight safety for the sake of economic expediency. I would propose, however, that it become a more useful tool for the aircraft designer and procuring agencies toward affecting better V/STOL aircraft in a real world environment. This can be accomplished, I believe, by considering more of the relevant factors involved.

Take, for instance, the fact that a pilot is fully capable of coping with aircraft instabilities as long as the time constants involved and the damping characteristics are within certain limits. This is not a novel idea. Fifty years ago, Charles Lindbergh flew across the Atlantic in 33-1/2 hours piloting an unstable aircraft. Moreover, he deliberately designed the instability into the aircraft to meet a specific need. He knew that the flight would be a long one, and that his chief enemy would be drowsiness and sleep. It makes little difference how much artificial stability you provide in a V/STOL aircraft if the pilot is the least bit inattentive during transition. Experience has shown that in V/STOL flight the prime emphasis must be on control rather than on stability; and if the pilot allows himself to reach a flight condition wherein his control becomes marginal, the artificial stability you provide is of small consequence.

The Harrier is certainly not considered to be the ultimate in V/STOL flying qualities. The pilot workload precludes IFR flight in the V/STOL flight regime and even VFR flight becomes less than satisfactory in turbulent conditions and in some flight operations at sea. The fact remains, however, that for normal VFR flying, it is a relatively easy aircraft to fly; and I believe that the experience gained in over 160,000 hours of squadron service can be utilized as a valid base for several changes to MIL-F-83300 which I will discuss herewith.

4. Basic Harrier Characteristics

Three of the stability characteristics which have been fundamental to the success of the Harrier are its very stable pitching moment break, Figure 6, its high level of spin resistance, and its speed stability during both accelerating and decelerating transitions, Figure 7.

The stable pitching moment break and high spin resistance allow short and sudden pitch excursions to high angles of attack without the aircraft exhibiting a significant tendency to get away from the pilot. These characteristics have also allowed the concept of thrust vectoring control (TVC) to be exploited as a survivability aid in a hostile air environment. For a ground attack aircraft, this capability is of inestimatable value, and has literally added a new dimension to the capability of the Harrier. Very rapid use of TVC at airspeeds from 500 knots down to as low as 70 knots at altitudes as low as 5,000 ft. is being employed in air combat maneuvering (ACM) tactics in the USMC today. Obviously, you don't do this type of flying if you are the least bit concerned about the departure characteristics of the aircraft.

The V/STOL flying qualities specification does not even address the need for departure resistance. It addresses warning of departure

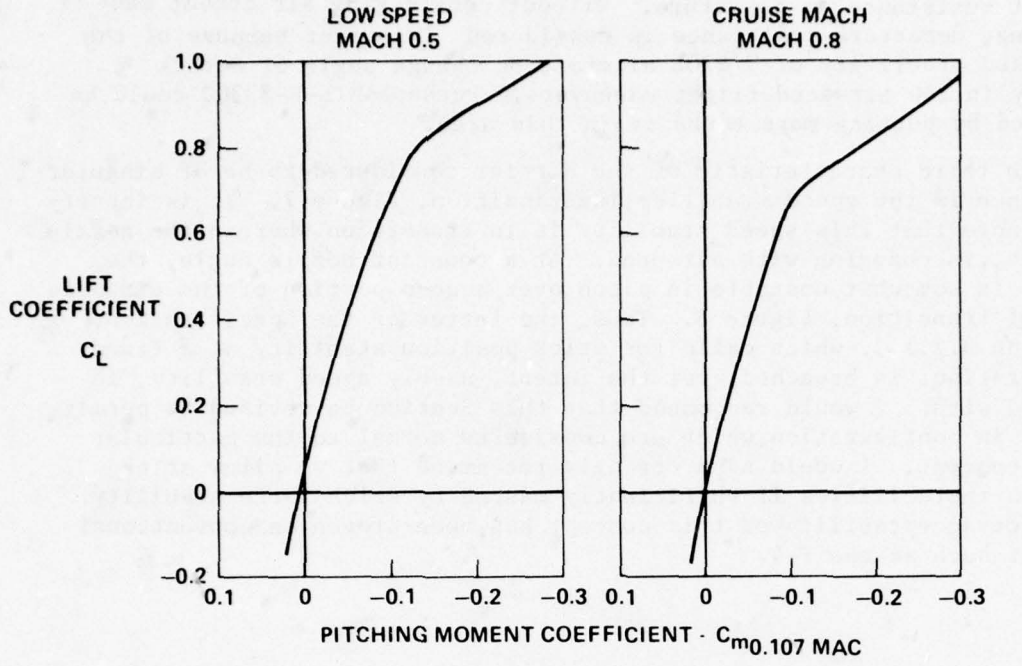


FIGURE 6
AV-8A LONGITUDINAL STABILITY

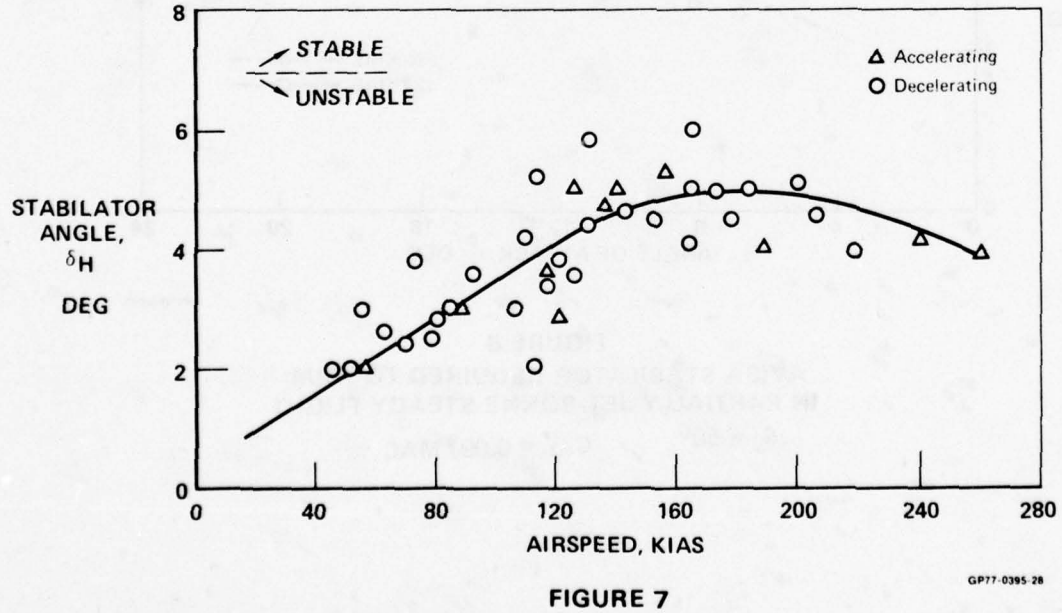


FIGURE 7
AV-8A SPEED STABILITY IN TRANSITION
$\alpha = 8^o$

but not resistance to departure. Without considering air combat maneuvering, departure resistance is considered important because of the increased proclivity of V/STOL aircraft to change angle of attack rapidly in low airspeed flight maneuvers. Perhaps MIL-F-83300 could be improved by putting more emphasis in this area.

The third characteristic of the Harrier considered to be of singular importance is the speed stability in transition, Figure 7. It is important to note that this speed stability is in transition wherein the nozzle angle, θ_j, is changing with airspeed. At a constant nozzle angle, the Harrier is somewhat unstable in pitch over a good portion of the airspeed range of transition, Figure 8. Thus, the letter of the Specification, Paragraph 3.2.1.3, which calls for stick position stability at a fixed configuration, is breached, yet the intent, namely speed stability, is complied with. I would recommend that this Section be revised to permit changes in configuration which are considered normal to the particular V/STOL concept. I would also strongly recommend that we allow stick position instabilities if sufficiently masked by stick force stability. The pilot acceptability of this concept has been proven on conventional aircraft such as the F-4.

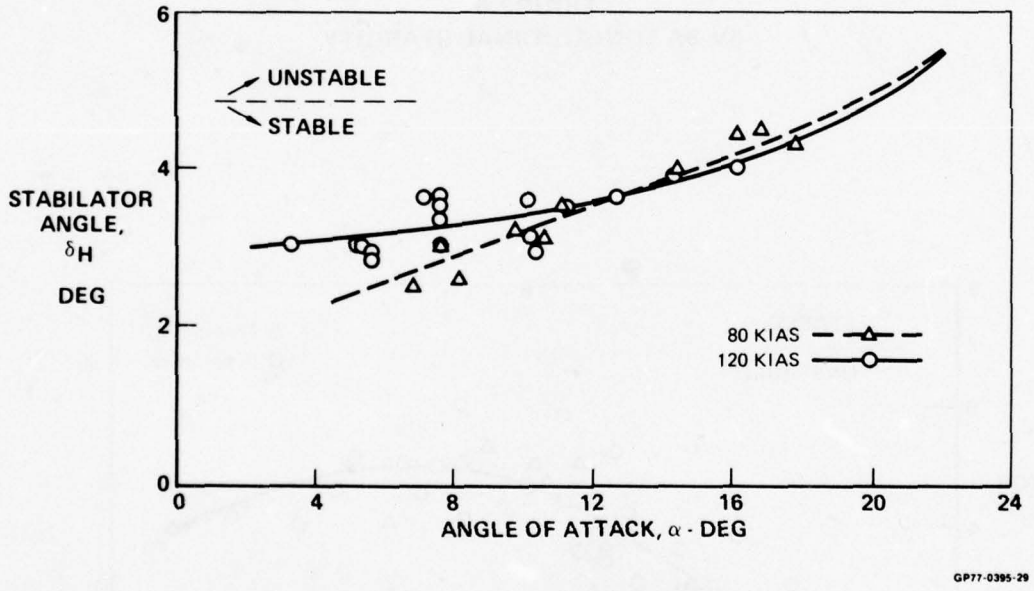


FIGURE 8
AV-8A STABILATOR REQUIRED TO TRIM IN PARTIALLY JET-BORNE STEADY FLIGHT
$\theta_J = 50^o$ C.G. = 0.097 MAC

5. Fixed Operating Point vs Transition

The need for a change in our emphasis in V/STOL from the fixed operating point (FOP) concept to the transition concept can be seen by looking at some typical Harrier transition data, Figures 9, 10, and 11. At the usual operating VTO gross weights the time from hover to fully wing borne, nozzles-aft flight is a mere 10 to 14 seconds. When one considers that this involves an acceleration from zero to approximately 140 knots one has to wonder about the justification for any requirement based upon a FOP type of analysis.

This questions takes on even greater significance when we look at some typical time histories of airspeed, nozzle position and throttle position obtained during VTO/accelerating transition and decelerating transitions, Figures 10 and 11, respectively. The decelerating transition, shown in Figure 11, is typical of standard operating procedures used in VFR flight by both the RAF and USMC on the Harrier. There is scant justification during either of these transitions for a FOP type of analysis.

The only V/STOL flight condition which approaches a FOP occurs in the slow landing approach in semi IFR conditions or in some types of carrier approaches. Even in these cases, however, the throttle and/or nozzle are seldom held at a constant setting, thus casting some doubt as to whether this condition should be looked upon as a true FOP condition. It is therefore recommended that the Specification put more emphasis upon the transition aspects of V/STOL flight and less upon conditions which are seldom realized in operational usage of V/STOL aircraft.

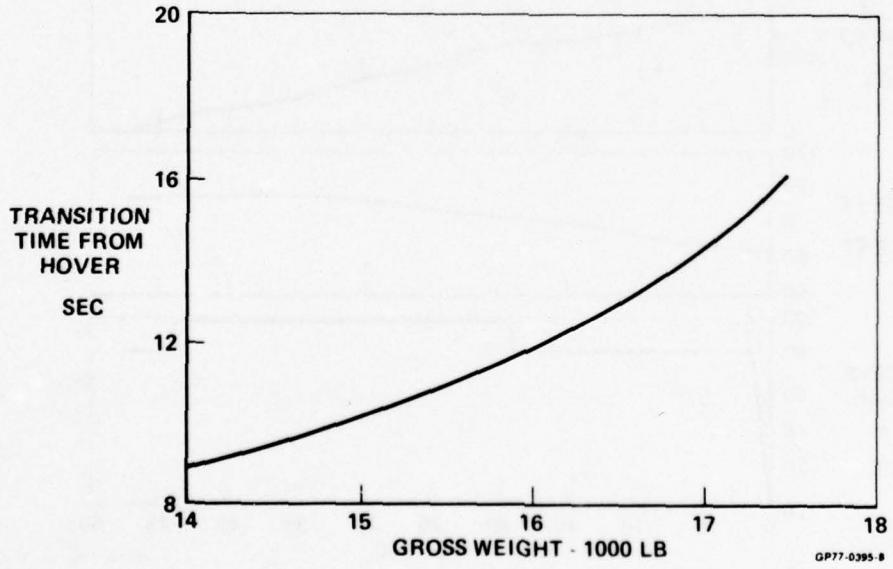


FIGURE 9
AV-8A TRANSITION TIME
SL Standard Day; SLW
$\alpha = 8^{o}$

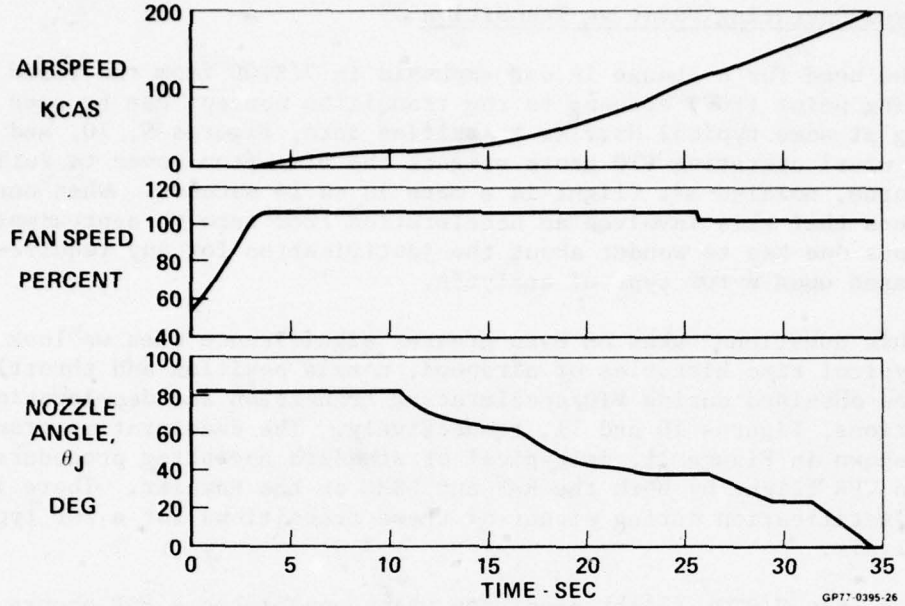


FIGURE 10
AV-8A VTO AND ACCELERATING TRANSITION
Gross Weight = 17,500 lb

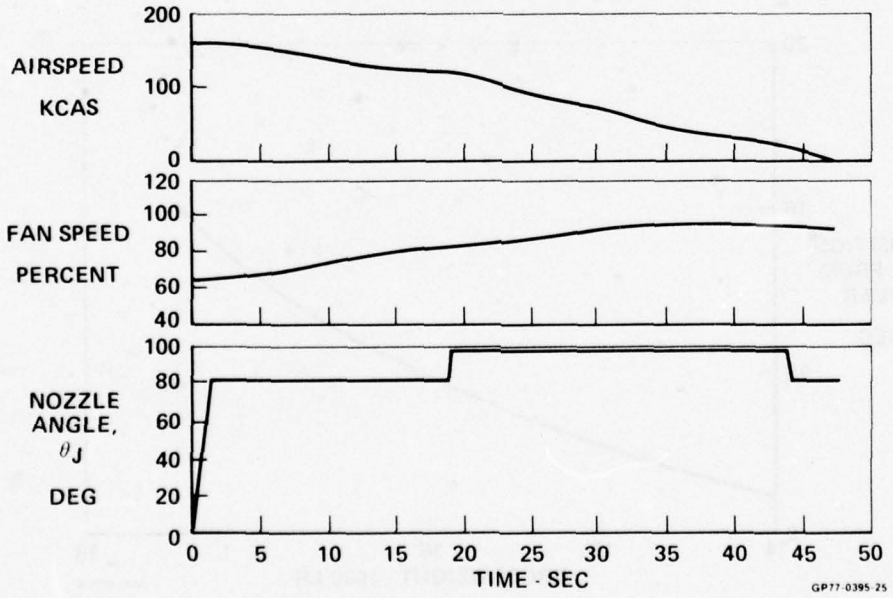


FIGURE 11
AV-8A DECELERATING TRANSITION TO HOVER
Gross Weight = 14,300 lb

6. The Pilot as SAS

Harrier flight experience has proven that both longitudinal and directional instabilities can be safely tolerated by pilot action without a stability augmentation system. Figure 12 shows the variation of both longitudinal and directional static stability of the Harrier with airspeed. Even though the aerodynamic characteristics are basically stable, the inlet momentum term produces a statically unstable aircraft up to certain airspeed levels. Since the majority of V/STOL configurations are faced with similar propulsion-induced instabilities, and since triply and quadruply redundant full authority SAS or CAS systems tend to be expensive both in initial cost and in maintainability, I would recommend that MIL-F-83300 be modified to permit statically unstable situations wherein the pilot can easily provide the stability. To automatically insist upon sophistication rather than simplicity as MIL-F-83300 presently does, is to stifle V/STOL progress and to ignore recent history, in my view. I'm sure many of you will not agree with this approach, but let me quote from the NPE, Reference (1), as regards the importance of SAS on the Harrier: "Simulated failure of the SAS during normal daylight flight was barely noticeable. Several unintentional SAS OFF accelerations, hovers, and vertical landings were conducted without the pilot noticing the lack of stability augmentation." And on the same subject: "The excellent SAS OFF flying qualities of the airplane enhance its suitability as a V/STOL airplane." These statements are not quoted to imply that there is no need for SAS on the Harrier, but it does show that V/STOL flight control systems need not always be as sophisticated as one might think.

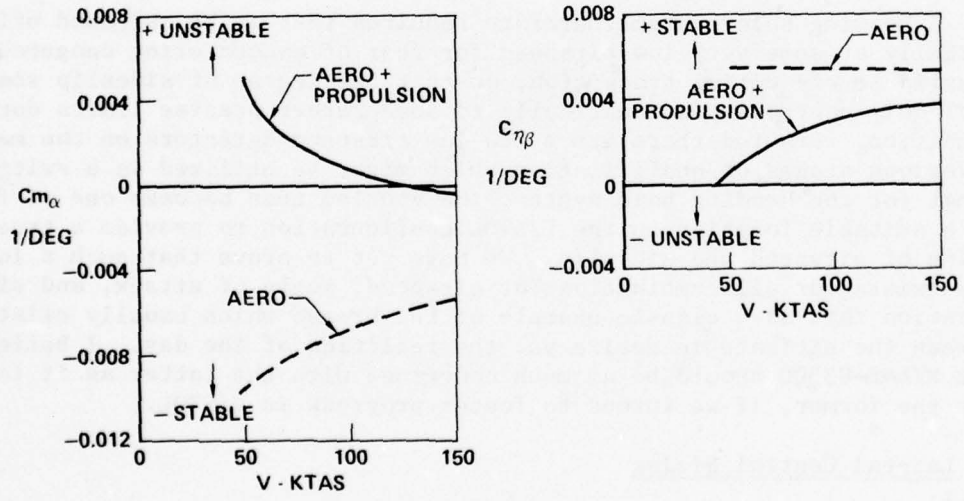


FIGURE 12
AV-8A VARIATION OF STATIC STABILITY WITH AIRSPEED
$\theta_J = 60^o$

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7. SAS Vs. State of the Art

I am not proposing that we should restrict progress in handling qualities; rather I am suggesting that we permit progress in V/STOL design within the confines of today's economic realities by putting the emphasis upon simplicity rather than upon complexity.

Our simulation studies at MCAIR show that the handling qualities of the Harrier can certainly be improved by the addition of a relatively simple attitude hold system in pitch and roll; and this is being pursued at the present time. There has also been some agitation for heading hold as well. We are not pursuing heading hold, however, for two very good reasons, namely: the complete system is considered to be too sophisticated, and it is not considered to be within the present technological state of the art.

The problem with heading hold is that what is good in hover is not necessarily good in transition. Most V/STOL configurations, including the Harrier, possess relatively high positive dihedral stability in the powered-lift mode, to the extent that lateral control power usually becomes the driving design factor in transition. This basic problem is well illustrated in Figure 13, which is borrowed from a recent paper by Mr. Robin Balmer, Chief Design Engineer for Hawker-Siddeley Aviation, Reference 2. In V/STOL flight, the combination of angles of sideslip and angle of attack, which are likely to be encountered, are substantially greater than those encountered in normal wingborne flight. This situation is generally compounded by the jet-induced effects in semi jet-borne flight which usually act to increase the dihedral effect. There is usually an airspeed range wherein the sum total of reaction control system and aerodynamic lateral control is inadequate to effectively counter the high rolling moment induced on the aircraft by a combination of high angle of attack and high sideslip.

A heading hold system therefore requires that it be switched off automatically at some very low airspeed for fear of encountering dangerous sideslip levels during transition, or that the degree of sideslip somehow be closely controlled automatically to some rather precise limits during transition. Granted there are a few low airspeed detectors on the market in various stages of qualification which might be utilized as a switchout signal for the heading hold system, the problem then becomes one of finding a suitable location on the V/STOL configuration to provide a true indication of airspeed and sideslip. We have yet to prove that such a location exists for all combinations of airspeed, angle of attack, and sideslip. I mention this as a classic example of the breach which usually exists between the ultimate in desire vs. the realities of the day. I believe that MIL-F-83300 should be as much concerned with the latter as it is with the former, if we intend to foster progress in V/STOL.

8. Lateral Control Sizing

The high dihedral-induced rolling moments mentioned above are responsible for the most significant flying quality limitation on the Harrier, namely, the relatively low lateral control margins which are available at combinations of positive angle of attack and sideslip in the speed range of 40 to 90 knots during transition. Yet the Harrier substantially exceeds the AGARD lateral control angular acceleration requirement, Figure 14, and the MIL-F-83300 roll attitude changes in one second, requirement,

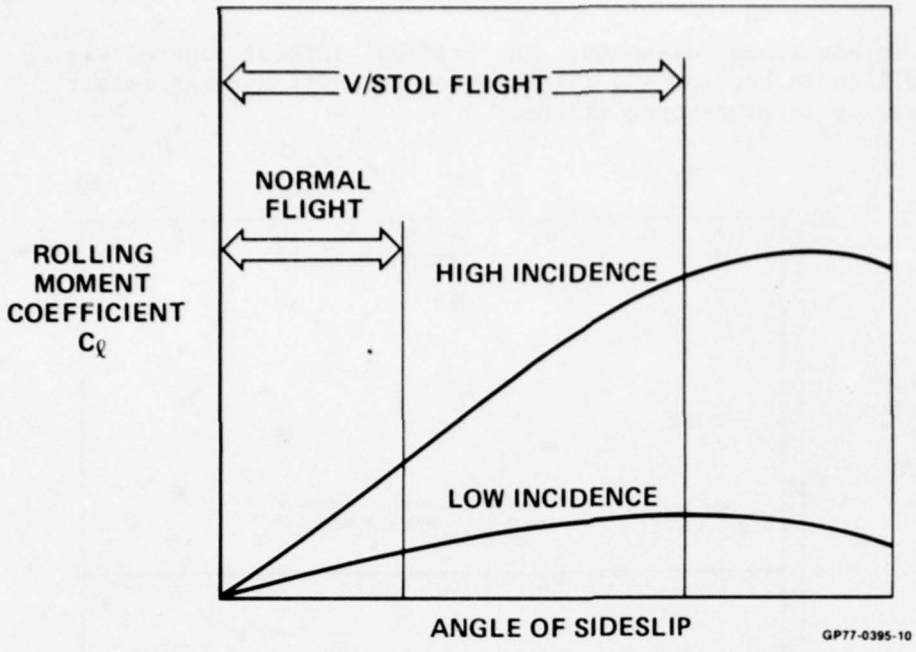


FIGURE 13
AV-8A ROLLING MOMENT DUE TO SIDESLIP

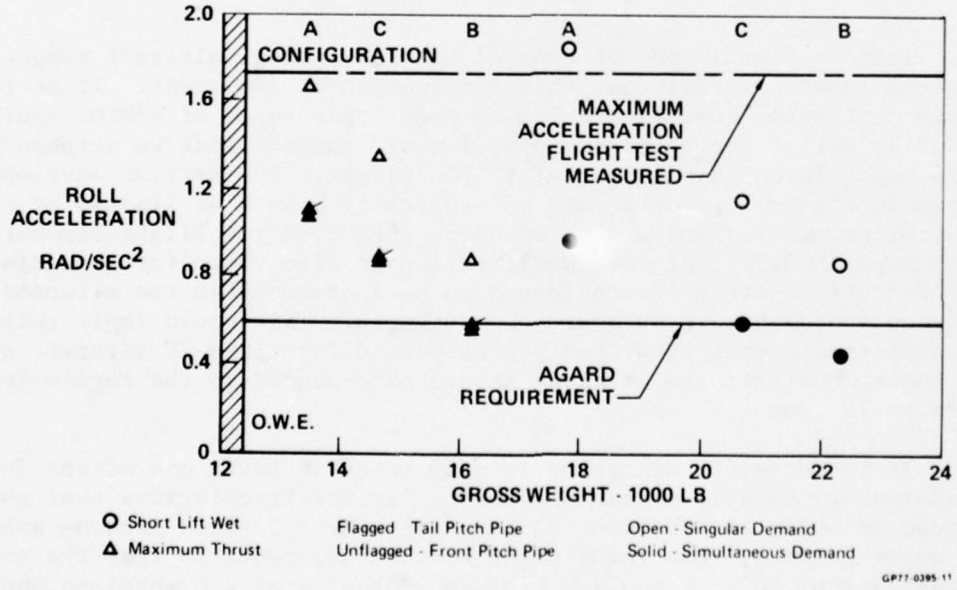


FIGURE 14
AV-8A REACTION CONTROL SYSTEM ANGULAR ACCELERATION CAPABILITY
Roll

Figure 15, in hover and low speed. The critical lateral control sizing point, then,lies in the low and intermediate transition range rather than in hover or in wing-borne flight.

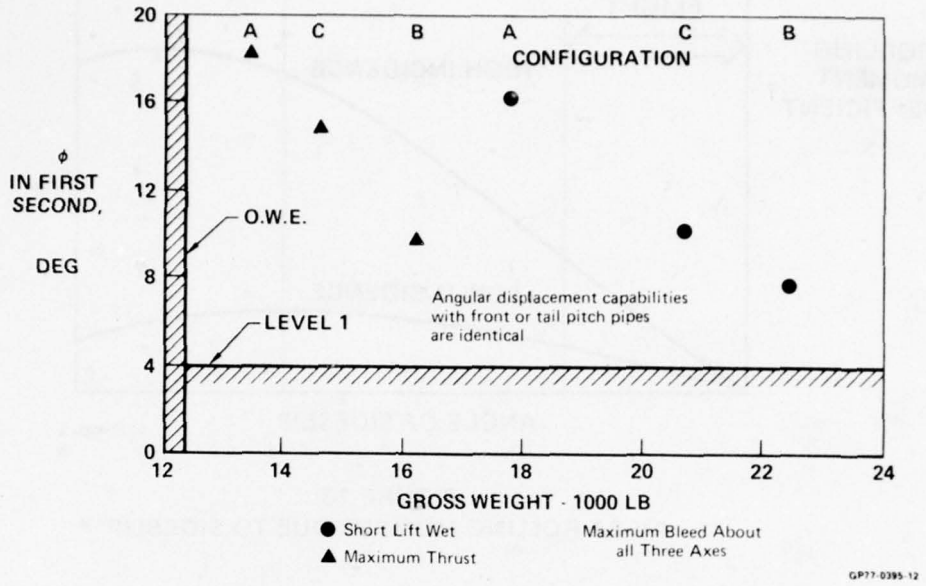


FIGURE 15
AV-8A REACTION CONTROL SYSTEM ANGULAR DISPLACEMENT CAPABILITY

This problem is one of control margins; not of aircraft response to control input. I feel that this distinction is important. It is the predominant lateral control problem on many other types of V/STOL configurations as well. For these reasons, I would suggest that we perhaps put more emphasis on this aspect of V/STOL flight. The Harrier envelope is shown in Figure 16, for 8° and 15° angles of attack as limited by lateral control power available. The envelope specified for flight demonstration in Paragraph 3.3.11 of the Specification is also shown for comparison. The Harrier envelope is considered to be inadequate in the airspeed region between approximately 40 knots to 120 knots. This would imply that the present requirement is probably pretty good for Class IV aircraft above 70 knots, but that the envelope should be expanded in the region from zero to 70 knots.

It is certainly necessary in many types of hover operations in headwinds to be able to execute purely lateral translations over the ground in order to position the aircraft over a desired landing spot. At zero airspeed, this requirement, of course, requires that the sideslip capability be 90°. I would therefore suggest that a β envelope where $\beta = \sin^{-1}$ 30/airspeed in knots would be a reasonable design goal.

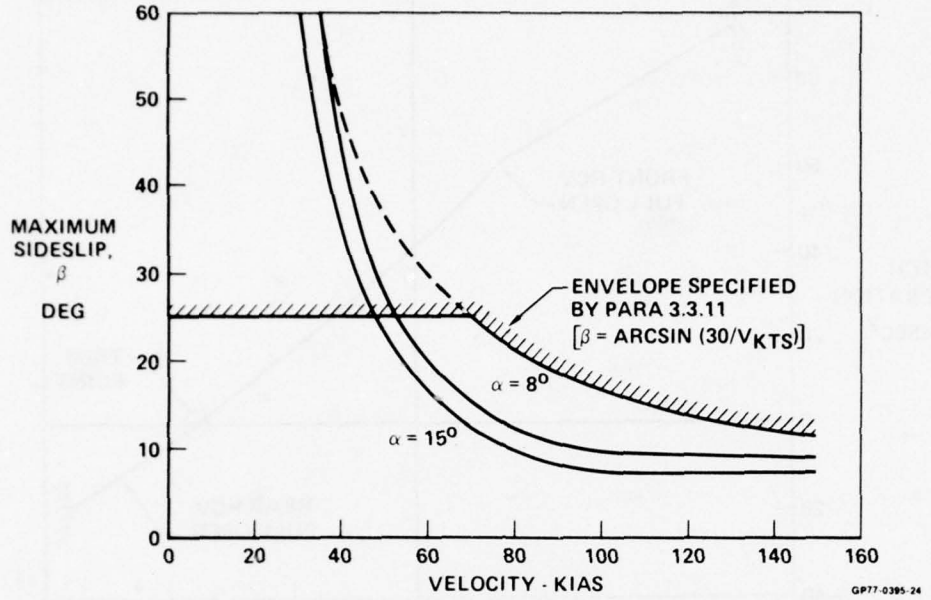


FIGURE 16
MAXIMUM SIDESLIP LIMITED BY FULL LATERAL CONTROL POWER

Another aspect of the roll-due-to-sideslip problem lies in the safety implications of the V/STOL flight demonstration program. As will be discussed in Section 13.0, much of V/STOL flying is very dependent upon pilot feedback from external visual cues. As a consequence, much of the V/STOL flight demonstration must be performed at relatively low heights (zero to 1,000 ft.). One might therefore question the safety aspects of demonstrating compliance with the requirements of Paragraph 3.3.9 which defines the minimum elapsed time to execute a 30° change in bank angle, or of Paragraph 3.3.11 which requires that certain levels of sideslip angles be demonstrated in the V/STOL flight region.

9. Longitudinal Trim

Perhaps the second most important handling quality problem on the Harrier lies in occasional instances of reduced longitudinal control margins which occur for some store loadings during shipboard STO's. Figure 17 illustrates the problem. It is one primarily connected with trim, however, rather than control power per se. Like the lateral control/sideslip issue discussed earlier, it is perhaps more important to stress that adequate control margins be maintained during transition maneuvers than to focus most of the attention on the capability of producing a given level of pitching acceleration in the hover. As shown for the particular configuration and flight condition of Figure 17, the limitation is not one of total control power capability; rather it stems from the distribution of that capability between the airplane nose-up and airplane nose down directions.

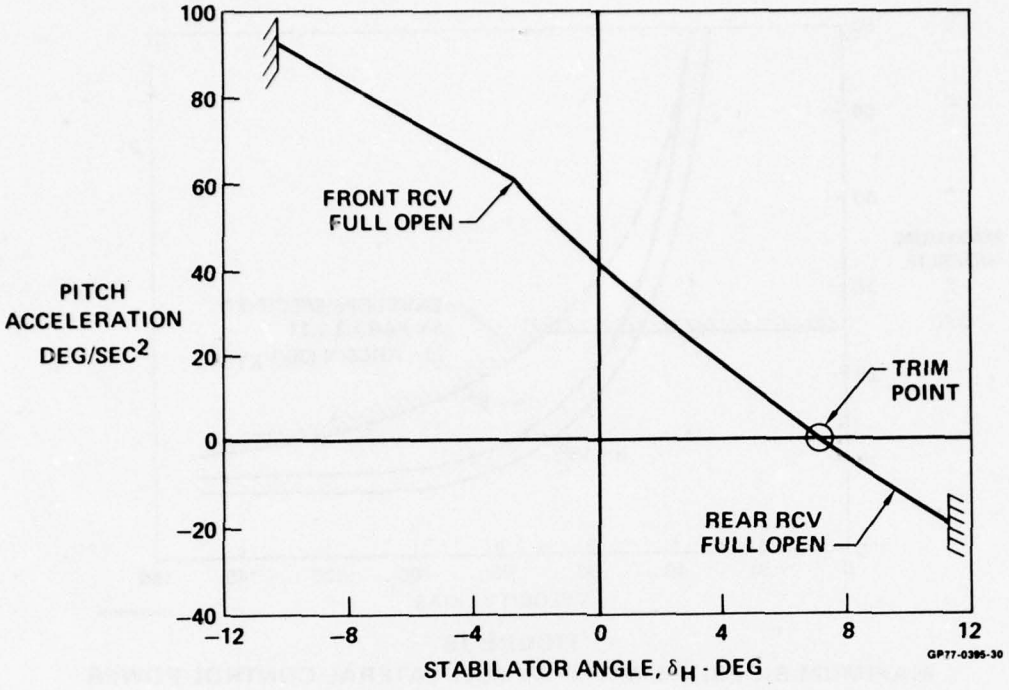


FIGURE 17
EXAMPLE OF LIMITED LONGITUDINAL CONTROL POWER IN TRANSITION FLIGHT

θ_J = 50-55 deg V = 120 kias Gross Weight = 19,450 lb

10. Control in Hover

The roll control in hover has already been discussed in Section 8. The pitch and yaw capabilities are compared to the AGARD and MIL-F-83300 requirements in Figures 18 and 19. respectively. The pitching requirements are met, however, the yawing requirements are not fully complied with. Since most pilots appear to be fairly happy with the Harrier's control power in yaw, at least as far as land-based VFR flight operations are concerned, it might be worthwhile to review the Specification with an eye toward reducing the levels required in hover. At least one other investigator, Reference 3,has indicated that the present requirements may be more demanding than necessary for satisfactory handling qualities.

One aspect of aircraft control in the hover which makes it somewhat distinctive from wingborne flight is that pilots prefer to separate roll control and responses from yawing control and responses in hover and low speed flight. Thus, a favorable rudder-induced rolling response which is considered to be of advantage in some regions of wingborne flight, is usually considered objectionable in the hover. It is therefore recommended that the Specification advise in Sec. 3.2 that control response interaction in the hover be minimized.

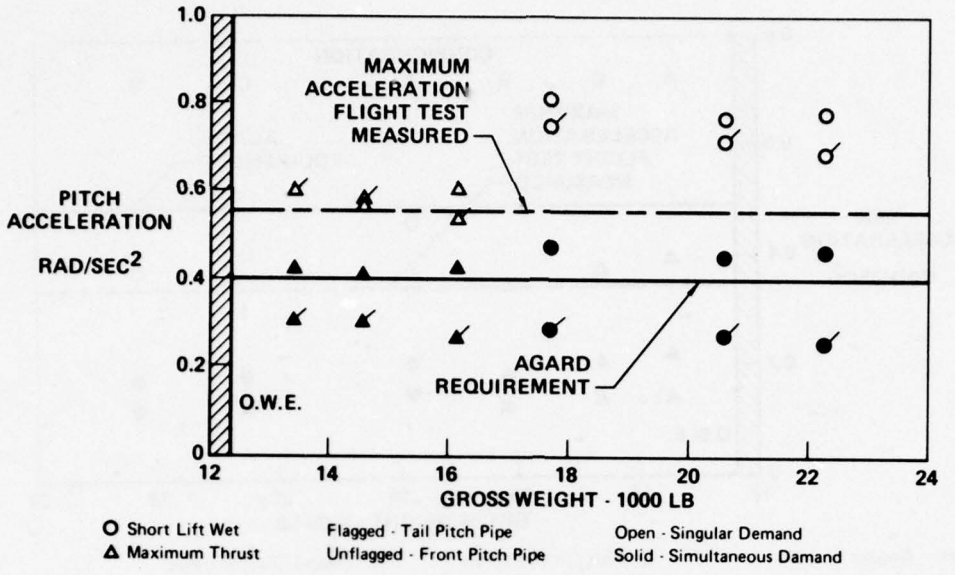


FIGURE 18a

AV-8A ANGULAR ACCELERATION CAPABILITY

Pitch

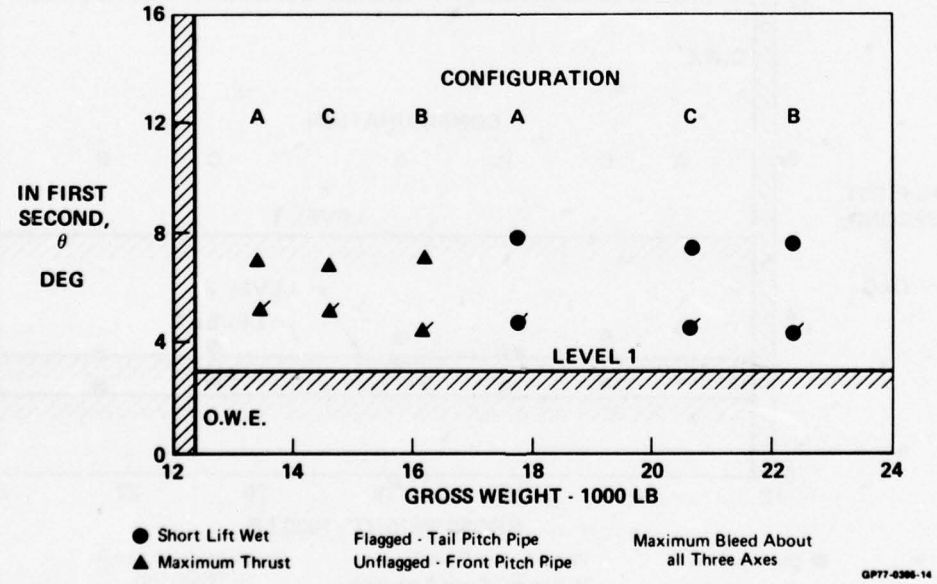


FIGURE 18b

AV-8A REACTION CONTROL SYSTEM ANGULAR DISPLACEMENT CAPABILITY

Pitch

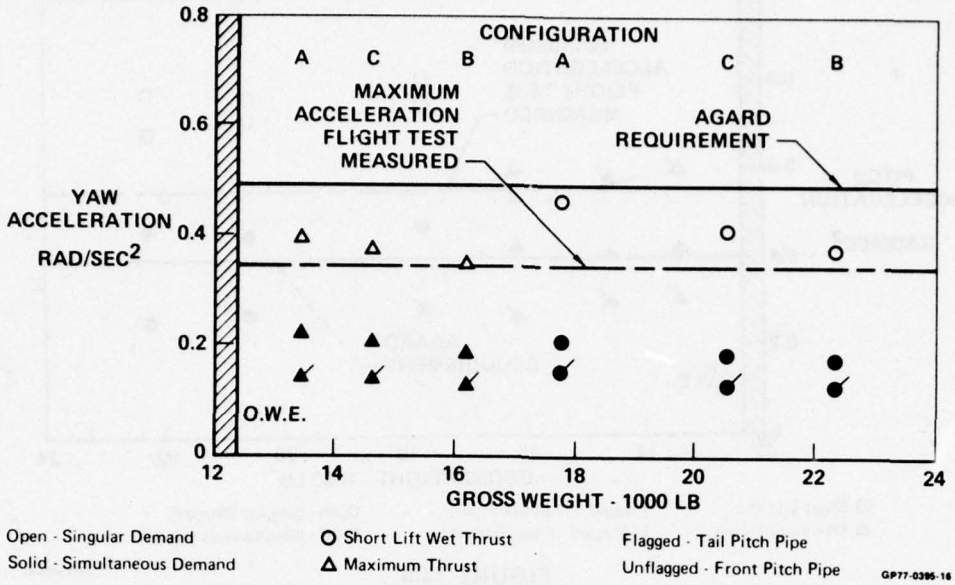


FIGURE 19a

AV-8A REACTION CONTROL SYSTEM ANGULAR ACCELERATION CAPABILITY

Yaw

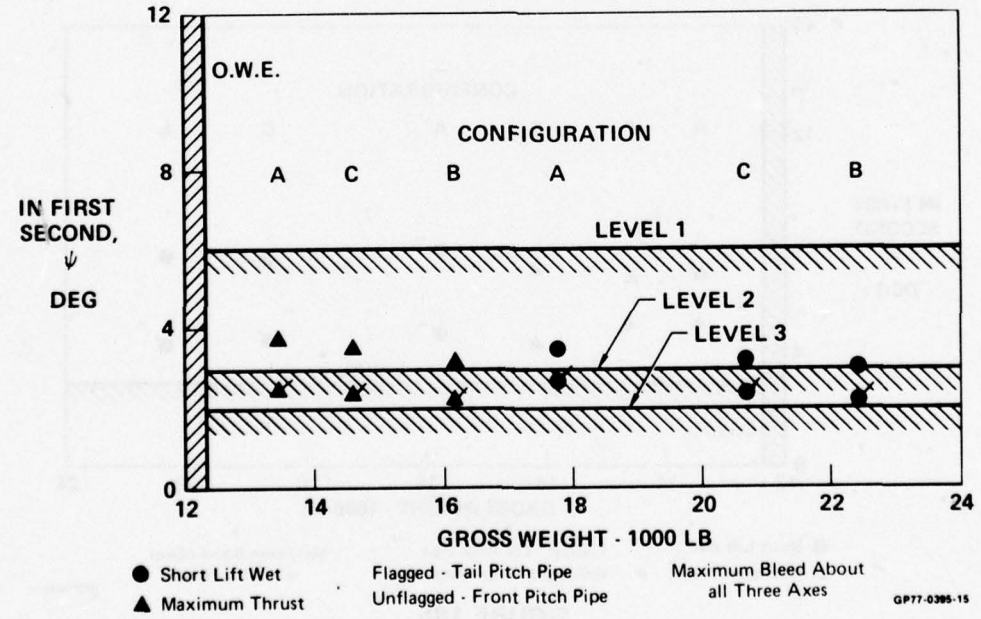


FIGURE 19b

AV-8A REACTION CONTROL SYSTEM ANGULAR DISPLACEMENT CAPABILITY

Yaw

11.0 Dynamic Stability

As implied in Section 5, it is believed that the very concept of dynamic stability at a fixed operating point needs to be reviewed as to its relevance to V/STOL flight. The stick fixed dynamic stability of the Harrier has been evaluated, however, for accelerating and decelerating transitions and for steady slow landing approach. These results are compared to the requirements of MIL-F-83300 in Figures 20 through 23. The short period longitudinal stability during accelerating and decelerating transition was evaluated SAS off for three different store loading conditions. It is seen in Figures 20 and 21 that, not only does the Harrier fail to meet the stability requirement, but it also fails to meet even Level 3 time to double amplitude requirements with the SAS turned off. Yet, the aircraft is relatively easy to fly in VFR flight operations without SAS.

The longitudinal short period response for the slow landing approach is compared to the Specification requirements in Figure 22 with and without SAS. It is seen that the damping characteristics are within the Specification with or without SAS at all airspeeds exceeding approximately 40 knots. The lateral-directional characteristics during slow landing approach are compared to the Specification requirements in Figure 24 with and without SAS. Level 1 requirements are not satisfied without SAS and are satisfied with SAS at airspeeds greater than approximately 80 knots only.

There are several reasons for questioning the relevance of the classic approach to dynamic stability in the powered-lift mode of V/STOL flight. First, among these is the fact that the oscillatory period of the so-called "short-period" mode becomes so long, Figure 24, that it approaches the levels usually associated with the phugoid response in wing-borne flight. In low speed vectored thrust flight on the Harrier, it is seldom that two or three seconds ever elapse without some sort of control change being made either in SAS-off or SAS-on flight.

Secondly and, perhaps, more fundamentally, the classic longitudinal dynamic stability analysis uses angle of attack variations with time as the prime variable in the short period mode with the phugoid mode being more of an altitude and airspeed variation at essentially constant angle of attack. In most areas of powered-lift flight the more significant factor in lift is the propulsive lift rather than the aerodynamic lift. Furthermore, as discussed in Section 13, the external visual cues as perceived by the pilot, are a fundamental part of the dynamic stability loop. Therefore one has to question whether N_θ might not be a much more relevant term for short period response than is N_α.

In any case, it is certainly difficult to assess the significance of the classic three dimensional stick-fixed approach to dynamic stability relative to the acceptability of aircraft handling qualities in vectored thrust flight at low airspeeds. One must also question the advisability of making the traditional stability envelopes hard and fast specification requirements without some compelling evidence that such analytically-derived characteristics are truly relevant to desireable handling qualities in the powered-lift mode of V/STOL operation.

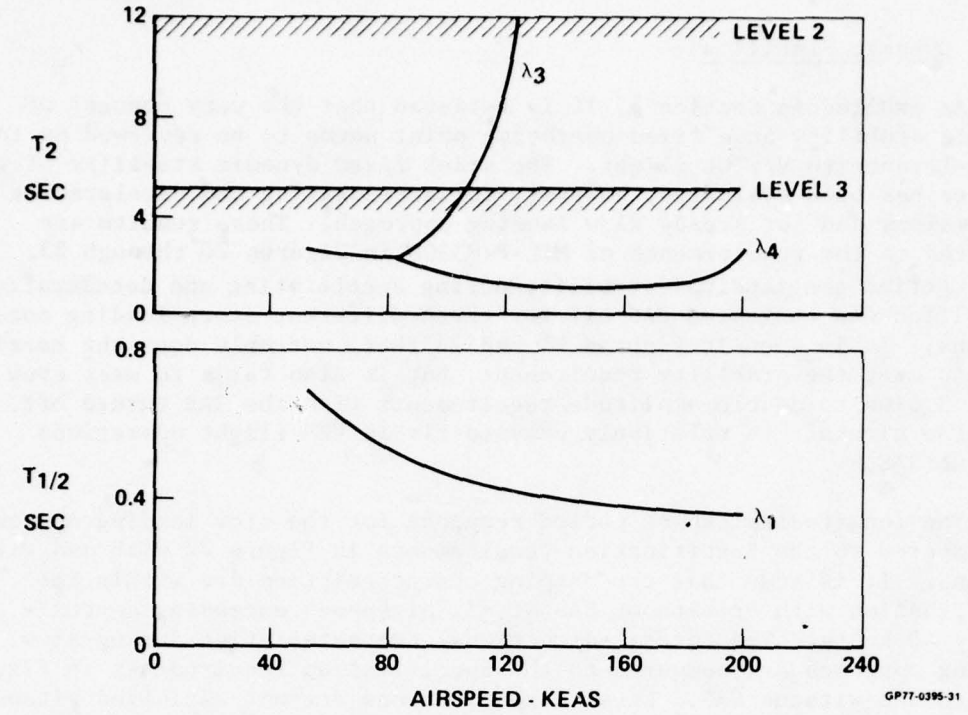


FIGURE 20
LOW SPEED LONGITUDINAL SHORT PERIOD RESPONSE
Accelerating Transition SAS Off

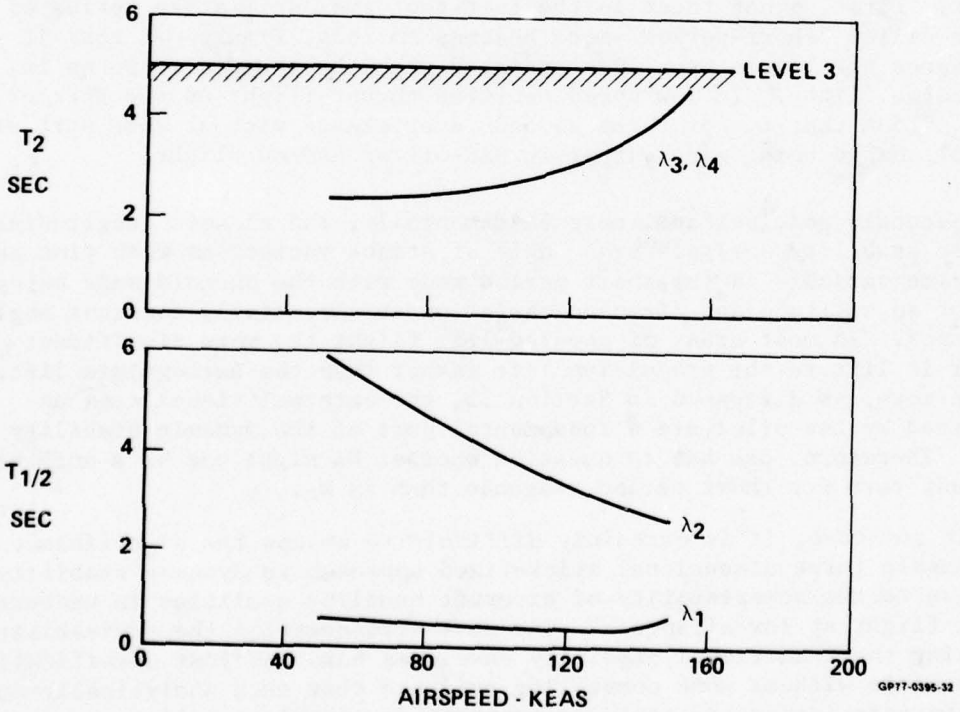


FIGURE 21
LOW SPEED LONGITUDINAL SHORT PERIOD RESPONSE
Decelerating Transition SAS Off

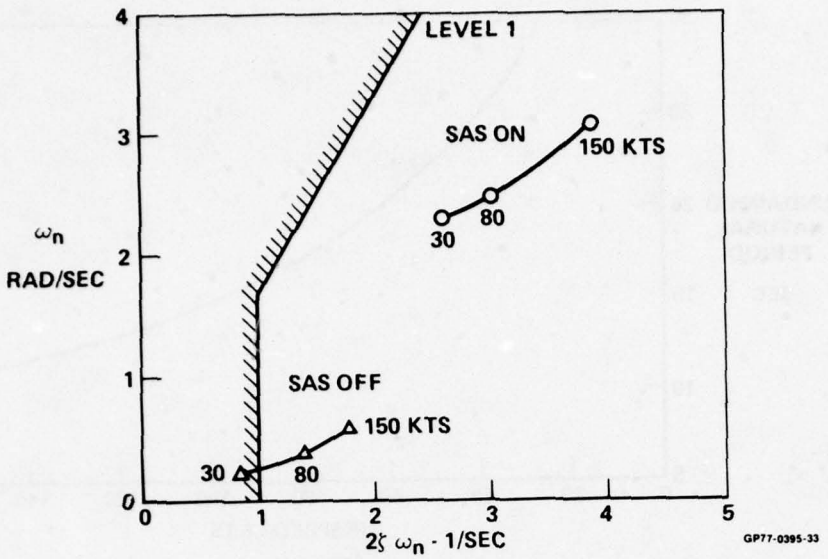


FIGURE 22
AV-8A LOW SPEED LONGITUDINAL SHORT PERIOD MODE
Slow Approach 15,500 Lb

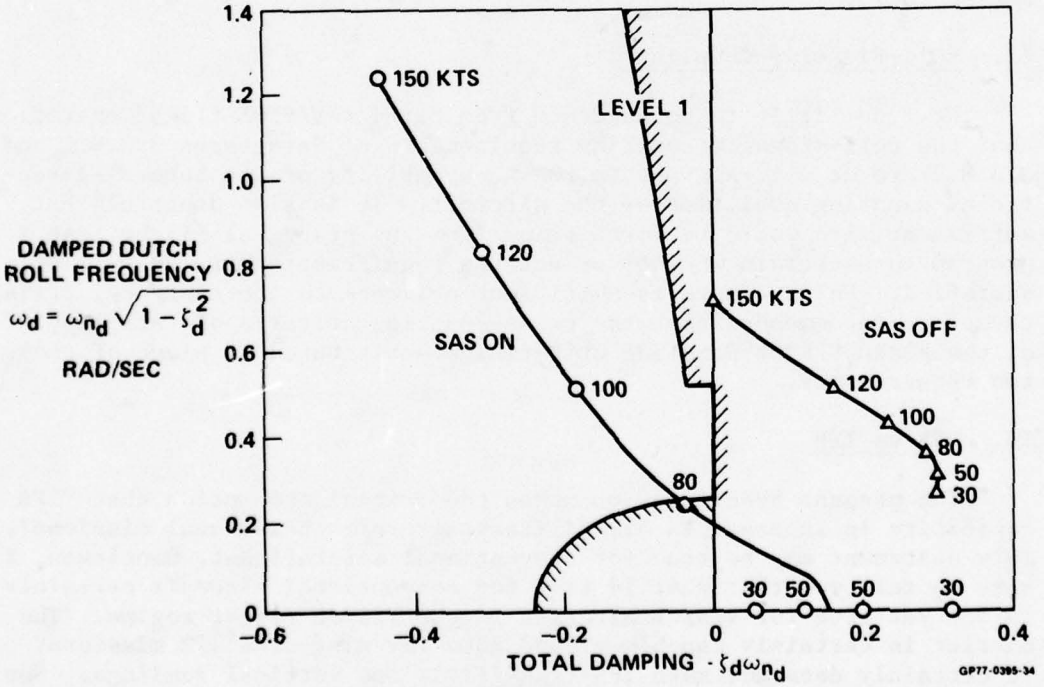


FIGURE 23
AV-8A DUTCH ROLL CHARACTERISTICS
Slow Approach 15,500 Lb

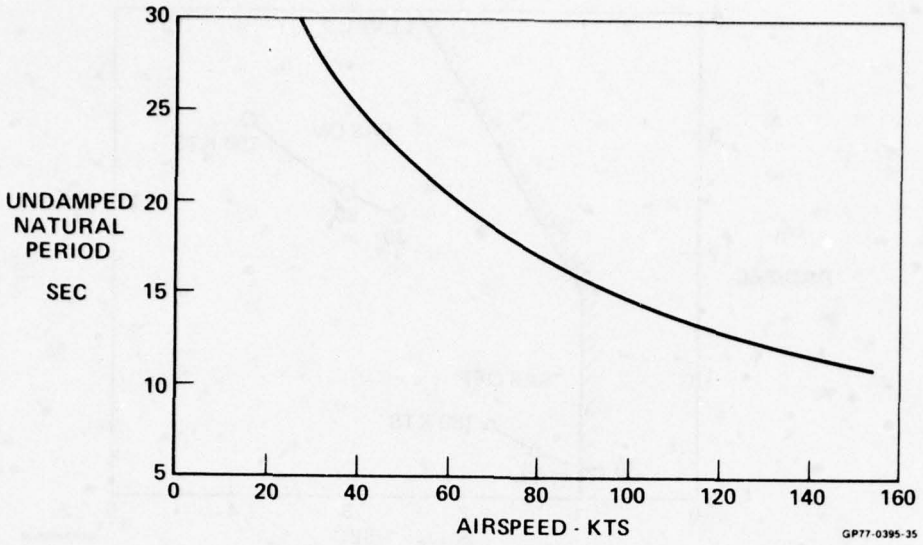


FIGURE 24
AV-8A SHORT PERIOD, PHUGOID OR SOMETHING ELSE?
Slow Approach SAS Off

In view of the many regions of non-compliance with the dynamic stability requirements by the free-world's only successful V/STOL aircraft, it is recommended that the traditional approach to specifying dynamic stability characteristics in V/STOL be reevaluated, and perhaps restructured.

12. Roll-Sideslip Coupling

We find little to no evidence from Harrier V/STOL flight operations that the roll-sideslip coupling requirements of Paragraphs 3.3.8.1 and 3.3.8.2 are at all relevant to the acceptability of the lateral-directional handling quelities of the aircraft. It is also doubtful that sufficient data would be forthcoming from any practical flight test program to ascertain whether or not the requirements were or were not satisfied. Unless there is sufficient evidence to the contrary, it is therefore recommended that the cross-coupling criteria of Paragraph 3.5 of the AGARD V/STOL Handling Criteria be substituted in place of these two requirements.

13. VFR vs IFR

The present Specification makes the initial assumption that "IFR capability is inherent in all military aircraft operational missions ...". This statement may be true for conventional aircraft but, Gentlemen, I'm here to tell you that what is true for conventional aircraft certainly is not yet true for V/STOL aircraft in the V/STOL flight regime. The Harrier is certainly capable of, and does fly wingborne IFR missions. It certainly does not make IFR transitions and vertical landings. Nor is it usually necessary to fly V/STOL under true IFR conditions. Many weather conditions requiring IFR in wingborne flight will still allow fully operational VFR for V/STOL flight since only 200 ft of ceiling and approximately 3/4 nautical miles visibility are required for transition in land based operations.

To the best of my knowledge all V/STOL flight to date has been conducted head-up; consequently, the importance of external visual cues cannot be overestimated (as anyone who has tried to conduct V/STOL simulations can readily attest). Therefore, to base a V/STOL flying qualities specification on IFR flight operations would appear to me to ignore the realities of our time.

I would submit that the Specification come to grips with the fact of head-up flying in the V/STOL mode of flight and recognize the importance and potential of a head-up display properly formated. The fact is that the pilot, his external visual cues and the head-up display are all integral and essential segments of the aircraft control and stabilization loop. Landing aid simulation studies conducted at MCAIR have indicated that substantial advances into the IFR flight domain are possible when the pilot is provided with the proper information on the HUD.

I would therefore recommend that we study these inter-relationships in flight simulators in order to provide the guidance which aircraft designers require.

14. Failure States

Paragraph 3.1.10.2 of the present Specification requires that the contractor determine "based on the most accurate available data, the probability of occurrence of each aircraft failure state per flight and the effect of that failure state on the flying qualities within the operational and service flight envelope". It goes on and on signing the contractor up for a matrix of studies which could theoretically break the bank at Monaco. The contractor has neither the staff nor the funding to handle the astronomical matrix which this paragraph of the Specification can be interpreted to cover. I believe it is necessary to address failure states, but in the interests of economic practicality, I would suggest that we address only those failures considered to be most significant and that we set a reasonable limit on the number of those cases.

15. Conclusions and Recommendations

In conclusion, we would like to list those aspects of MIL-F-83300 which are considered to be productive from an aircraft design standpoint and those which we would assess as requiring some change or deletion. Finally, we would list our recommendations for improvement.

Those aspects of the present Specification which serve as valuable guidelines to the designer are as follows:

- o Delineates and addresses the vital V/STOL flight regimes without being unduly restrictive
- o Summarizes a large amount of V/STOL flight experience
- o Provides guidance for flight control system design
- o Provides some guidance for aircraft dynamic flight response characteristics

- Classifies aircraft and addresses flying qualities according to specific mission requirements

Characteristics of the Specification which we would assess as needing revision are as follows:

- Does not adequately recognize the stability augmentation capabilities of the pilot
- Tends to be overly conservative, particularly in the yaw mode
- Relies too much on helicopter experience at very low airspeeds and on MIL-F-8785B during transition
- Too much emphasis on fixed operating points and not enough on transition requirements
- Too much emphasis on angular acceleration capability in hover and not enough on maintaining adequate control power margins
- Does not address V/STOL flight in today's frame of reference, namely, as a completely head-up VFR flight operation
- May not fully recognize the safety implications of certain flight demonstration requirements
- Does not recognize the practical limitations of today's economic environment
- Addresses yaw requirements as to sideslip producing capability rather than sideslip reducing capability
- Does not adequately consider two of the basic problems associated with most V/STOL configurations, namely: high C_{L_β}'s and the instabilities due to inlet momentum.

Recommended changes to the Specification are as listed below.

- Change requirements to design guidelines in regions not supported by conclusive data
- Allow instabilities which can be handled adequately by the pilot
- Address head-up displays as an integral part of the control and stabilization loop
- Distinguish between VFR & IFR flight requirements
- Expand transition section
- Replace Paragraphs 3.3.8.1 and 3.3.8.2 with AGARD Section 3.5 on Cross Coupling following an abrupt roll control input.
- Review flight demonstration requirements for consistency with flight safety

- o Address importance that external visual cues play in acceptability of handling qualities in VTOL; include cockpit visibility guidelines

- o Through pilot-in-the-loop simulations, revise the dynamic stability criteria for better compatibility with V/STOL flight

- o Limit failure state analysis to a realistic number of conditions

- o In hover and low speed address the importance of minimizing interactions among the pitch, roll and yaw control responses

- o As a design guideline stress the importance of simplicity and good high angle of attack characteristics as a foundation for V/STOL

In summary, it is believed that the many thousands of successful squadron flight hours already accumulated on the Harrier provide us with a fertile data base which could be utilized to influence a revision of the MIL-F-83300 V/STOL Flying Qualities Specification. This experience would suggest that several changes be made both in the approach to obtaining better V/STOL Handling Qualities and in the specific design guidelines themselves.

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DISCUSSION

Charles Abrams: I have a few little points to ask you regarding the simplification of the flight control system while at the same time calling for increased complexity in display systems. Shouldn't there be a tradeoff point between the flight control and display that is determined by the worst flight conditions in an IFR situation? Admittedly, one can't make any statement about the tradeoff between flight control and displays until one has considered them for the worst flight conditions. There must be a tradeoff involved.

Lacey: Yes, I agree. My view on that, within the confines of the Harrier experience, is that we haven't fully recognized or incorporated the full capability of the relatively simple HUD display. Certainly there must be a tradeoff, but at present it is a little hard to say what the optimum situation is. I think that we may be leaning, at least in my view, to "over complex-i-sizing" the stability augmentation system, and many of the displays which are necessary are being overlooked in that loop. As far as the worst case, I'm sure that we can make many advancements, but those advances do cost money. In addition, everytime one designs more complexity into the vehicle, one takes a risk of degrading the maintainability and reliability factors.

Abrams: Although the aircraft has an initial capability, if it flies only 50 percent of the time, it isn't a very useful vehicle. You must have the complexities in the flight controls as much as you need displays, providing the mission is being performed under the worst situation. Those situations won't be laboratory conditions, but more likely could be combat conditions. You have to give them (the pilots) all the help you can.

Lacey: I certainly wouldn't disagree with you, but trying to provide that in today's economic environment is very difficult. We have attempted over the last three years to interest the customer with many different types of improvements. They show great interest until they see the price tag. And when they (the customer) see the price tag, that's the end of it. I think that you're going to find that to be the situation more and more in the forseeable future.

Duane Simon: We seem to have set up a dichotomy of sorts. On the one hand, the VAK-191 apparently met most of the specs with a conclusion that it was the best flying aircraft. On the other hand, your aircraft (the Harrier) failed to meet 17 of the specs and yet it flies well. I understand that you're suggesting that we allow these vehicles to be designed to a more relaxed situation relative to the specs.

Lacey: I think that you almost have to because I don't think we're that smart in V/STOL yet. I think it's the kind of thing that has to be worked out between the manufacturer and the procuring agency. I just don't believe that a lot of the specification requirements at present are relevant. Certainly many of them are, and the Harrier would certainly be a better aircraft to fly if it met some of those that it does not presently meet. But there are other specs that I think just aren't very relevant. In fact, some of these might even work to the detriment of the aircraft.

Daniel Cichy: I'm still interested in just where the deficiency is in the display. Is it in regard to the information of the airplane airspeed and

attitude, or is it in regard to the landing aids which are needed for IFR use?

Lacey: You mean the Harrier display?

Cichy: Sure.

Lacey: Well, there are quite a few items involved in the display question and it's almost too involved to fully cover at this time. For example, items such as the pilot's eyeball position relative to the HUD itself is not too good. The format of the display could be improved quite a bit for the situation of V/STOL IFR operations. You can add certain things to it that are not on there right now as well. At present, I don't believe that the average Harrier pilot uses the HUD very much during his V/STOL approach.

Irving Ashkenas: I'd like to raise the issue of the "operating-point stability" vs. the "transition stability" by remarking that I think the type of stability you are seeing on your transitions are applicable to a so-called canned approach under VFR conditions including fairly favorable weather that differs from the Navy's requirements by a long way. Now part of the reason for wanting a so-called "point stability" is to allow the pilot the option to proceed down the transition corridor in other than a crash approach fashion with the capability of backing up, looking around to make sure everything is OK and not being committed to going through the transition all at once.

Lacey: Good point, Irv.

Sam Craig: Your curve (Figure 22) showing dynamic stability includes two boundaries. Could we show that slide for a second? You show one boundary "SAS-off" and another boundary "SAS-on". The Harrier has a very limited authority SAS. Where are you really operating?

Lacey: This dynamic stability analysis was done within that very limited case based upon the assumption of not saturating the SAS. It is easy to saturate the SAS on the Harrier since, as you pointed out, it is very limited in authority.

Craig: I just wondered, based upon your operational experiences, whether you had gathered any data relative to where you're really operating as far as the pilot workload is concerned?

Lacey: Well, we fly with both the SAS-off and SAS-on. But under a VFR type of flight, when it's not too turbulent, the addition of SAS has not been that noticeable. The only point I want to make is that the pilot does supply a lot of stability.

LTCOL ILES: I'd like to caution you gentlemen against generalities. I haven't really seen too many familiar principles that didn't apply in the final analysis. I would feel a little reluctant to leap right in and state, based upon one set of data, that you want to change the specifications. It is my opinion that you need to get very specific, by task and environment, prior to reaching a decision for changing something.

Lacey: I think that's an excellent point. The requirements do change very rapidly with task in the V/STOL environment. The IFR condition, the true

V/STOL IFR condition, is a very difficult operation which in my opinion is going to require considerable sophistication, especially if one wants to bring the aircraft all the way down to the deck. From the experiences that we've had over the last four or five years, we've come to recognize that such sophistication is outside today's economic reality. But that's another problem, I guess.

CDR Hornblower: You've been mainly talking about the AV-8A. Could you tell us a bit about what you're hoping to improve with the AV-8B?

Lacey: I'll just make a few statements. We are going to increase the lateral control capabilities in transition and hover by approximately 75 percent which would allow compliance with the envelope drawn in the present specifications down to 70 knots. We are also concentrating in the area of maintaining equal nose-up and nose-down longitudinal control in all our trim conditions. We have made some real progress towards that end. I'd say that those are the two major items that we've been addressing. We hope to have a better HUD eventually, and we think that will be a big improvement over what is available now. We're looking at improved over-all cockpit design as well. All these items combine in a pyramidal effect and I think will be quite noticeable in the AV-8B. We're not making any real fundamental changes, rather we're going in a direction to be most cost effective.

Dale Hutchins: I might add that the AV-8B, in the way it's defined right now for the Marines, is still a VFR operational system. It is not a Navy shipboard airplane.

V/STOL HOVER STABILITY IMPACT ON HOVER CONTROL TASK

BY

A. B. Whitaker, C. P. Kelly, R. B. Wittman and R. P. Martorella

Grumman Aerospace Corporation

Existing V/STOL flying qualities specifications and AGARD Design Guidelines address the required control power and attitude response in some detail. Since these requirements are necessary, but not sufficient to develop a V/STOL aircraft with good handling qualities, additional design criteria must be specified. This is usually done with a simulator on which different control systems are evaluated by pilots until adequate systems improvement has been achieved as defined by a satisfactory pilot (Cooper-Harper) rating.

Our first experience with this hover task was with the Apollo Lunar Module which was a hover and vertical landing craft. Several years ago we studied landing on small ships with our V/STOL Design 674 Nutcracker. In all cases, the pilot ratings were initially very poor with conventionally designed attitude control systems. However, when outer loops were closed to provide for translational velocity control, very good pilot ratings were achieved. This has led us to take a more critical look at the hover to landing phase of VTOL flight with some very interesting conclusions. First, however, lets examine normal flight where it is agreed that good flying qualities criteria exist.

Conventional Flight

In conventional flight the normal aerodynamic stability provides a trimmable speed stability. In fact, the paragraph in MIL-F-8785B which excludes airspeed periodic divergencies is titled "Longitudinal Static Stability." This association of static stability with speed stability can be illustrated by the simplified transfer functions shown on Figure 1. Here the short period mode (SP) translates the control command δ_c into a new angle of attack (α). This new α disturbs the phugoid mode (ρ) and produces a new velocity (u). This separation of modes is useful to the analyst but can obscure the fundamental contribution of the static stability to the control of velocity.

The basic longitudinal static gain of the aircraft control system is shown in the lower part of the figure. When the gains of the two modes are combined we find that C_{m_α} and C_{L_α} produce the term $\partial C_m / \partial C_L$ the aircraft static stability. This term appears in the denominator so that, as the static margin is reduced ($\partial C_m / \partial C_L \rightarrow 0$), the static system gain for the control of velocity becomes very large. The system becomes very sensitive and all ability to trim velocity is lost.

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If the static stability is lost the constant term of the short period mode becomes zero. This changes the fundamental control characteristic. Now, it is necessary to pulse the controls to change the velocity rather then simply retrimming them. The most dramatic impact of the loss of aerodynamic stability is the response of the aircraft to air turbulence. The outside disturbances appear as control pulses resulting in velocity diverging in a random manner. The pilot cannot anticipate these disturbances and must continually correct for them. His workload becomes excessive.

This explains why MIL-F-8785 insists on speed stability in the name of longitudinal static stability. When a high workload task must be performed by the pilot, such as vertical landing in bad weather on a small ship, this speed stability is very important. Can we afford to settle for less in hovering flight for Type "A" V/STOL?

Hovering is primarily a translational velocity control task and is usually performed close to the landing site. The velocity which is important is the relative velocity between the aircraft and the planned touchdown point. The airspeed approaches zero and is of little use because the principal component of the airspeed is the air turbulence. Under these conditions the aerodynamic stability of the vehicle becomes negligible. The aircraft control characteristics take a form similar to the conventional flight without static stability. The static gain from control command to velocity appears infinite. The control characteristics require pulses to command a finite velocity response, and air turbulence causes the velocity to diverge in a random manner. The presence of air turbulence places a high task loading on the pilot just to maintain hovering flight. For all practicable purposes the vehicle appears unstable and untrimmable.

Providing attitude stability to the aircraft will not rectify the situation as it did in normal flight. Without aerodynamic stability the phugoid mode is reduced to a simple integration which behaves like a static instability in the velocity control. To maintain one's position in hover, the acceleration forces produced by the thrust and gravity must be nulled. This places a very stringent requirement on attitude which must be commanded to null lateral accelerations or an independent thrust vectoring must be used for the same purpose. This attitude control required to null the accleration forces involves smaller angular corrections (a small fraction of a degree) than the pilot can sense. The pilot can only sense the resulting velocity divergence and continually correct it. In turbulent air this becomes a very difficult task requiring a high degree of pilot training and a large portion of the pilot's attention.

If the pilot is to perform a high workload task such as vertical landing on a small ship at night in bad weather then the system must be stabilized. Since velocity is the quantity to be controlled, velocity sensing and feedback is the answer.

Translational Velocity Control

Since at hover we have no aerodynamics to do our work for us, we must close a control loop on velocity to achieve a stable, trimmable system. Figure 2 shows the effect of a simple velocity control loop. The short period attitude response of the vehicle $G_{\theta(s)}$ is so rapid compared to the velocity response that it can be assumed to be equal to 1 for this discussion. This assumes a stable damped attitude control loop. The velocity feedback loop then converts the untrimmed acceleration which produces a velocity divergence to a first order velocity command system.

This system provides the concept of basic static speed stability in hover. Such a system has speed trim capability. It meets the fundamental intent of MIL-F-8785 speed stability criteria when the pilot needs it the most during landing. It results in a significant reduction in pilot workload. It accomplishes this by returning to the pilot direct command of velocity without the need for anticipation. In addition, it completely changes the aircraft's response to turbulence by eliminating any tendency to drift from the desired position and reduces the magnitude of the resulting transient displacements.

It's no wonder that the pilots give very good ratings to systems with translational velocity control in the prescence of air turbulence. We are supplying a fundamental stability and control characteristic which all landing control systems should have.

Simulation Study

In order to verify the significance of the above discussions a six degree of freedom man-in-the-loop low speed simulation study was made using the Grumman Research simulator. A description of this simulator with its translational and rotational capabilities is shown in Figures 3 and 4. Using both experienced and unexperienced pilots the main objectives of the study were:

- To evaluate a specific hover task which was to move from position A to B, pause, and place a nose probe in a target
- To evaluate two control systems, namely attitude rate command and translational velocity command
- To evaluate the pilots' performance with and without turbulence.

Experienced Pilot Results

The experienced pilot had over 8000 hours in helocopters ranging from the small Bell-47G to the large CH-53E. The simulation task with a non-turbulent environment was relatively easy with both control systems as seen from the forward and lateral velocity traces in Figure 5. The pilot gave the task a Cooper-Harper rating of 3.0 using the attitude rate command system and 2.5 using the velocity command system. The Cooper-Harper rating is

based on a range of 1 to 10 where 1 is excellent and 10 is uncontrollable. The only indication in the figure which implies that he was working harder when using the attitude rate command system is his control motions which are a continual series of pulses. He would command a nose over attitude to start moving forward, then constantly oscillate the stick to maintain an approximately constant forward velocity. This technique would be expected since his controller pulses command acceleration and he is visually and mentally closing the velocity control loop. Although the ratings were close, he indicated that this may be the case only because of his large flying experience, and suggested that an inexperienced pilot would have difficulty flying the rate command while almost anybody could fly the velocity command system.

The case with turbulence presented much more difficulty for him when using the attitude rate command system. His longitudinal and lateral velocity traces were not as uniform for the non-turbulent case and his control inputs were larger and faster (Figure 6). He gave the task a rating of 7.0. His performance with the velocity command system as related to task completion and control difficulty remained essentially unchanged from the case of no turbulence. His rating of 2.5 being the same as the non-turbulent case reflected this.

Inexperienced Pilot Results

The inexperienced pilot used for the simulator study is a non-professional pilot with some private flying experience and a substantial amount of Grumman simulator flying experience. For the non-turbulent case he was capable of completing the task with both control systems (Figure 7), however, he found vehicle control relatively easy with the velocity command system. For the turbulent case using the rate command system the vehicle was uncontrollable. When using the velocity control system even the inexperienced pilot's performance was little affected by the air turbulence as shown in Figure 8.

Conclusion

These results indicate that the attitude rate command system because of its inability to trim translational velocity does not provide good spot hovering capability and would be a difficult type of control system to use for a precision spot hover task such as landing on a small ship in a rough sea. On the other hand, a translational velocity command system will provide vehicle control relatively free of translation due to turbulence enabling the pilot to make precise movements, provide good spot hovering capability and reduce the pilot workload.

Therefore, we recommend that a requirement for speed stability be added to MIL-F-83300, for high task loading conditions such as Type "A" V/STOL all-weather landing on small sips. Based on the speed stability

from MIL-F-8785B, Para. 3.2.1.1 "Logitudinal Static Stability," we propose adding the following paragraph titled

> STABILITY WITH RESPECT TO SPEED IN HOVER AND LANDING.
> THERE SHALL BE NO TENDENCY FOR THE RELATIVE VELOCITY BETWEEN THE AIRCRAFT AND THE LANDING PLATFORM TO DIVERGE APERIODICALLY WHEN THE AIRCRAFT IS DISTURBED FROM TRIM.

In addition, a statement should be added to define the magnitude of the allowable displacement resulting from a velocity disturbance. This will define the dynamic response necessary for the velocity control to be effective in reducing the pilot workload.

CONVENTIONAL AERODYNAMIC STABILITY

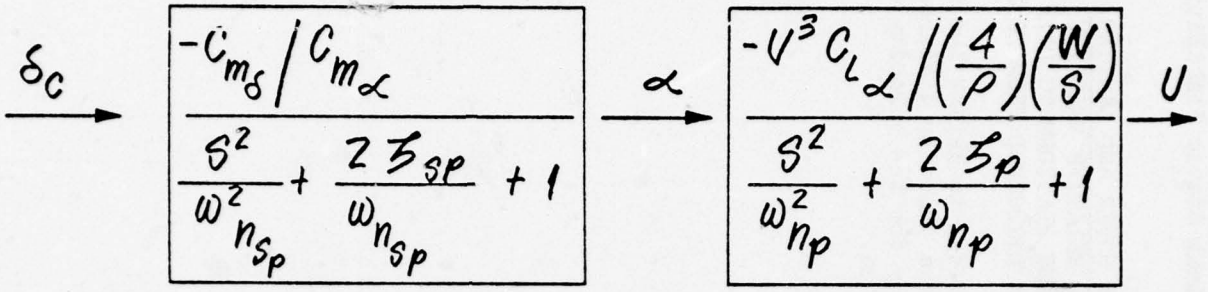
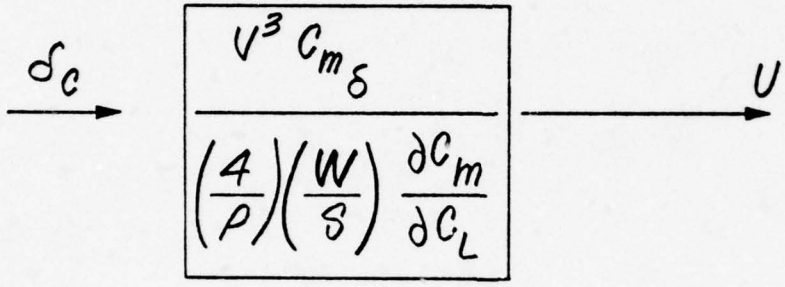
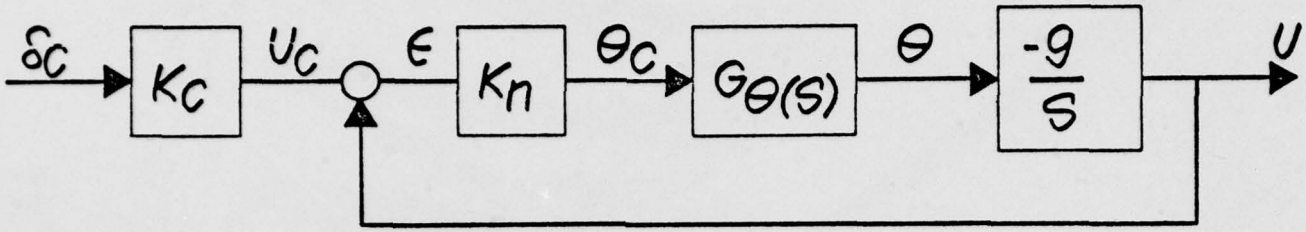


FIGURE 1

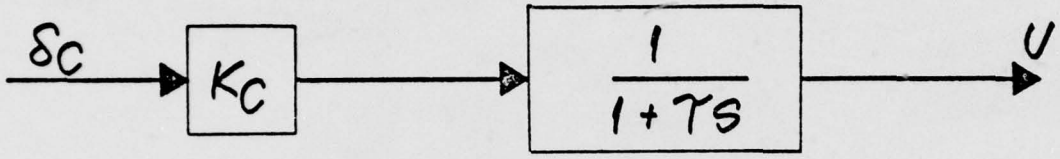
STATIC SYSTEM GAIN



TRANSLATIONAL VELOCITY SENSING THE ANSWER



RESULTS IN



WHERE $T = K_n G_{\theta(S)} g$

FIGURE 2

6 DOF MOTION SIMULATOR

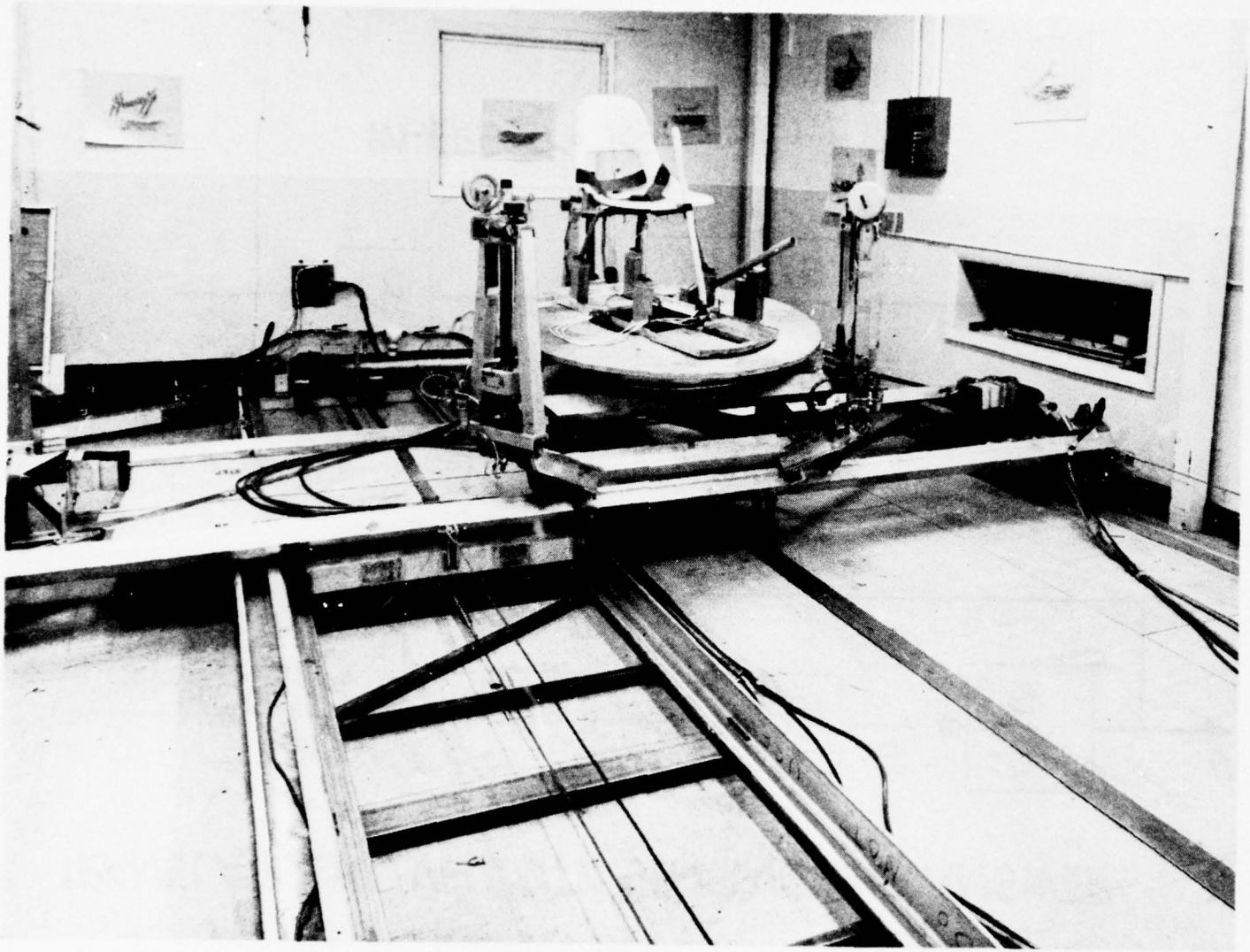
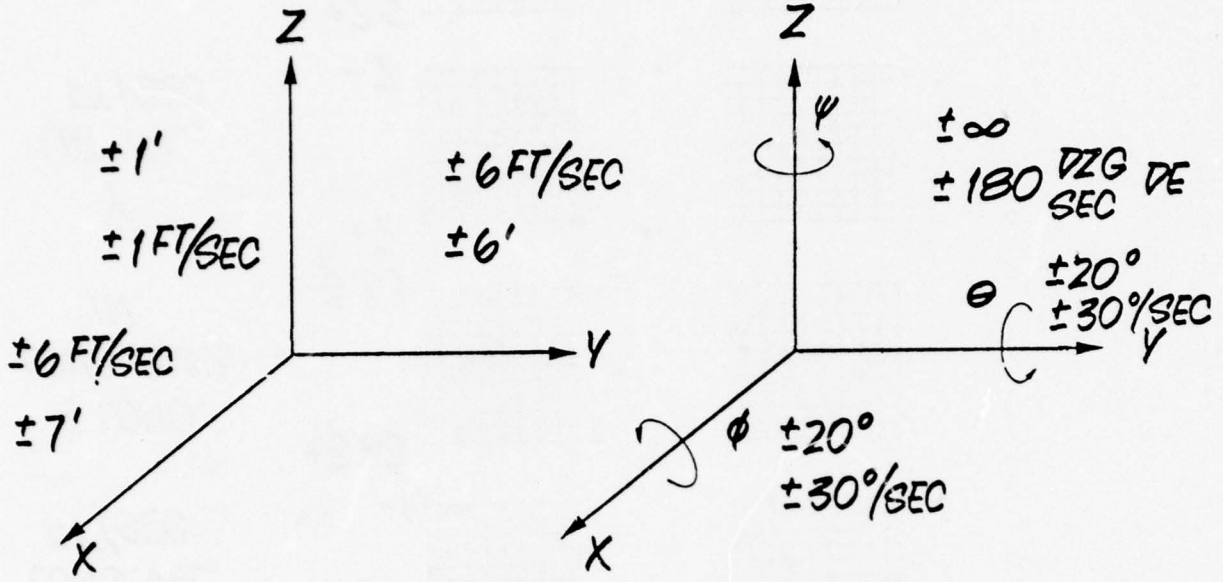


FIGURE 3

6 DOF MOTION SIMULATOR PERFORMANCE



PAYLOAD LIMIT 300 LB

FIGURE 4

EXPERIENCED PILOT - SMOOTH AIR

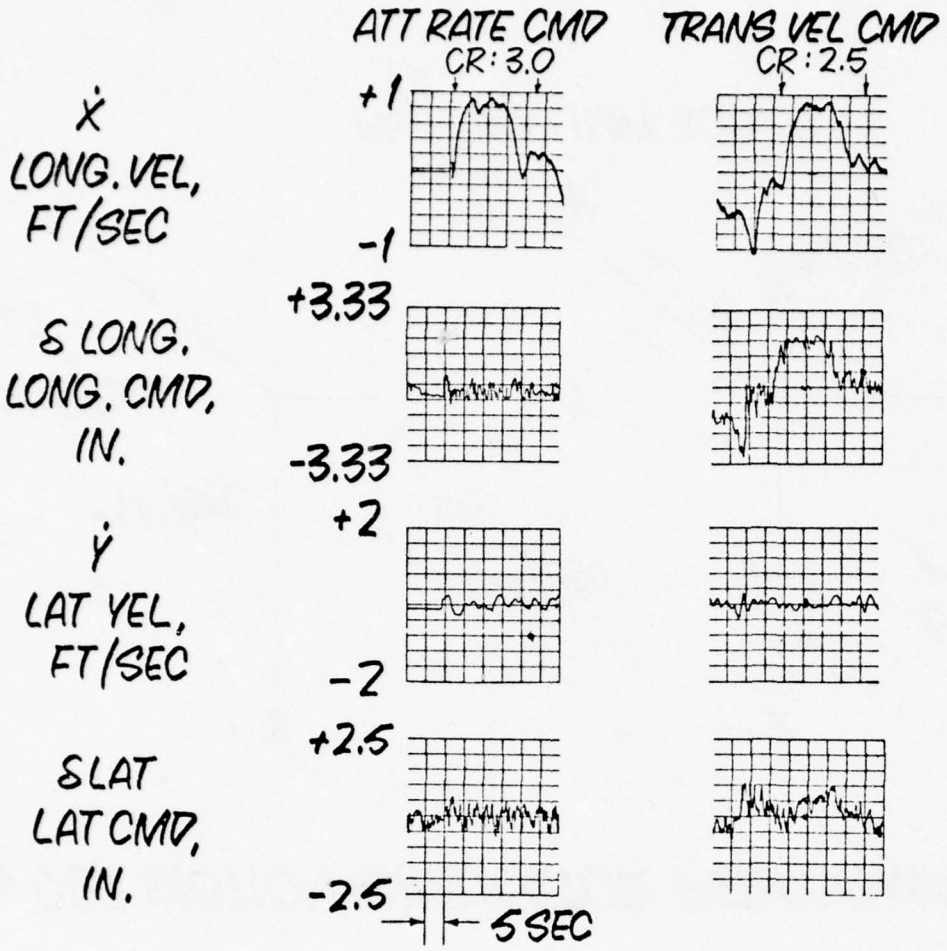


FIGURE 5

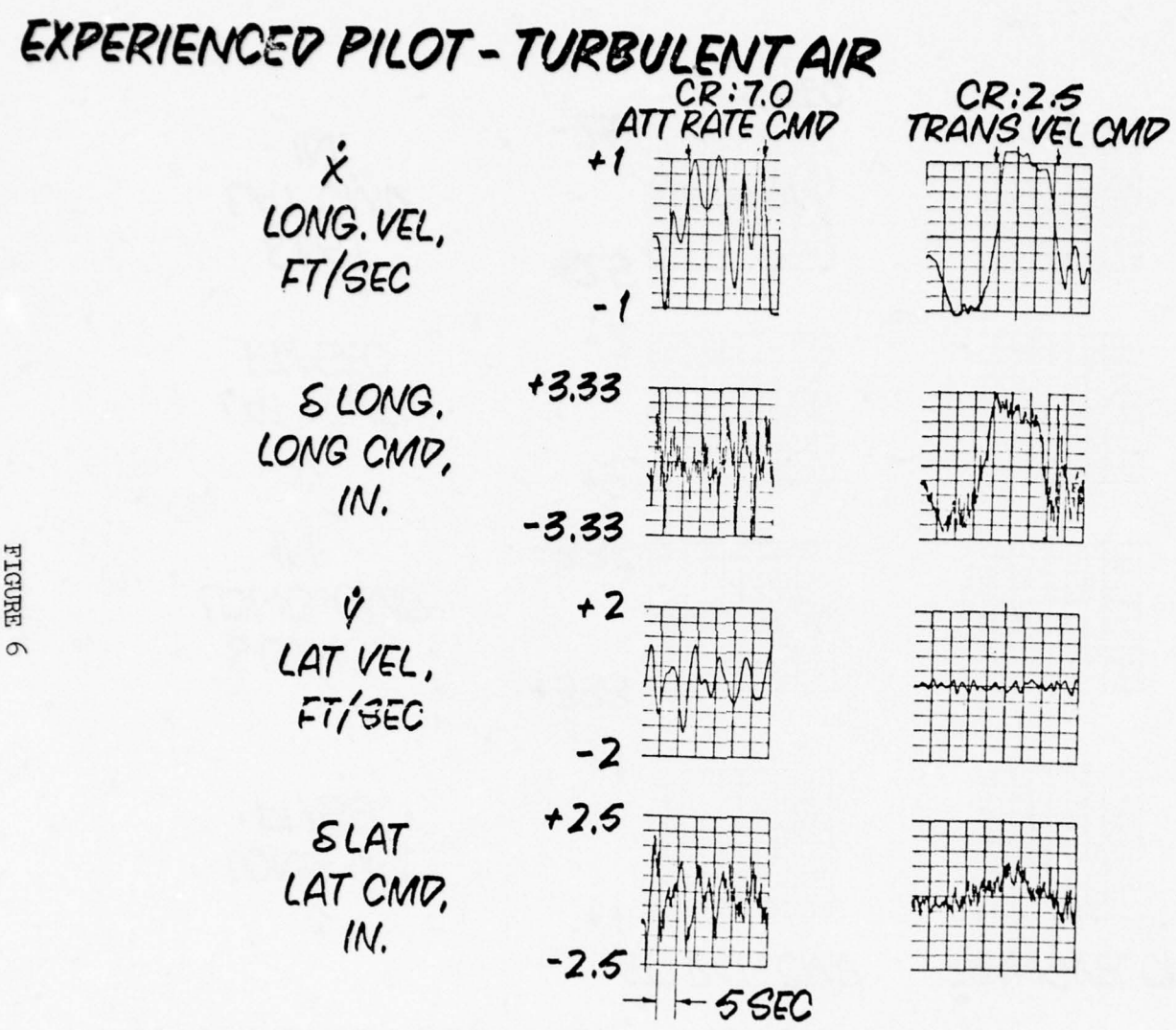

EXPERIENCED PILOT - TURBULENT AIR
CR:7.0
ATT RATE CMD
CR:2.5
TRANS VEL CMD
$\dot{x}$
LONG. VEL,
FT/SEC
+1
-1
δ LONG.
LONG CMD,
IN.
+3.33
-3.33
$\dot{y}$
LAT VEL,
FT/SEC
+2
-2
δ LAT
LAT CMD,
IN.
+2.5
-2.5
5 SEC

FIGURE 6

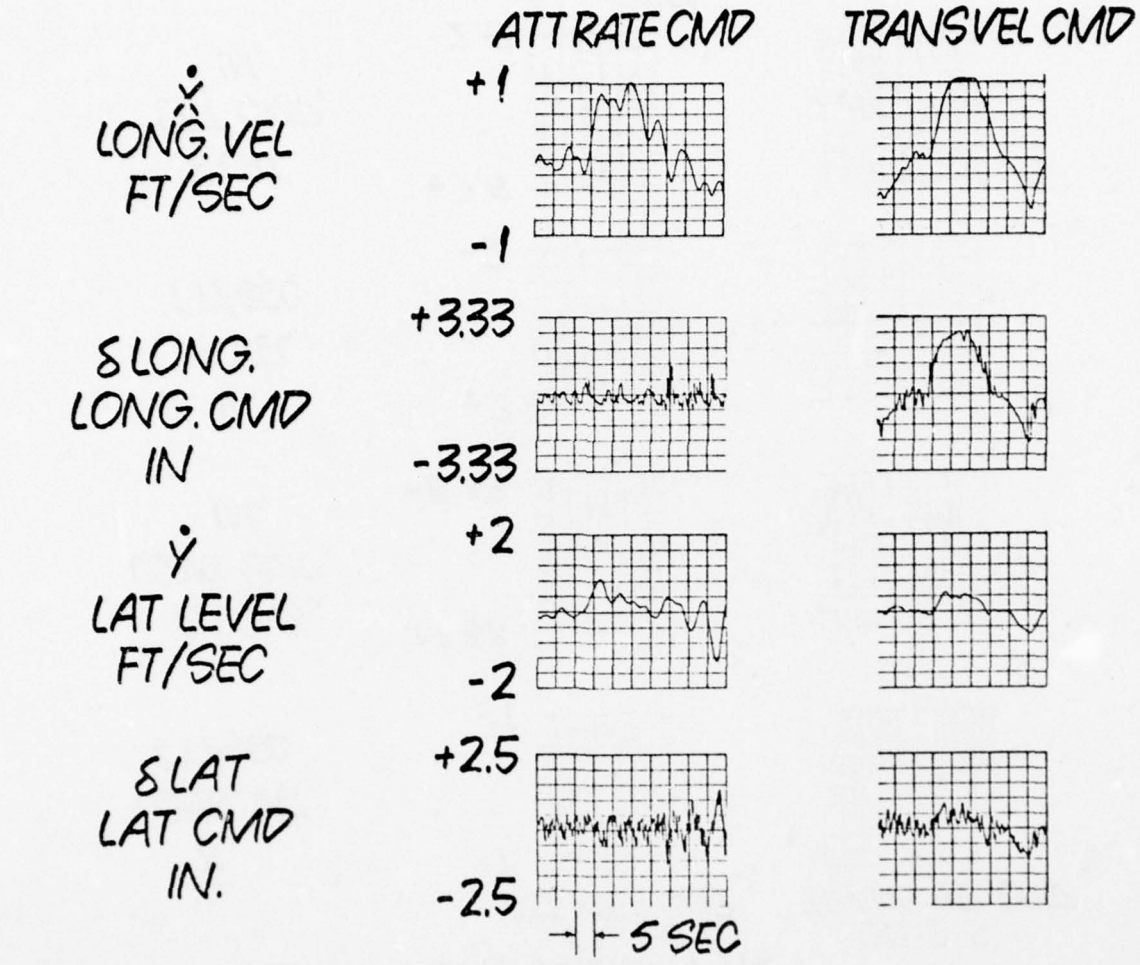

INEXPERIENCED PILOT - SMOOTH AIR
ATT RATE CMD
TRANS VEL CMD
$\dot{v}$
LONG. VEL
FT/SEC
+1
-1
δ LONG.
LONG. CMD
IN
+3.33
-3.33
$\dot{y}$
LAT LEVEL
FT/SEC
+2
-2
δ LAT
LAT CMD
IN.
+2.5
-2.5
5 SEC

FIGURE 7

INEXPERIENCED PILOT TURBULENT AIR

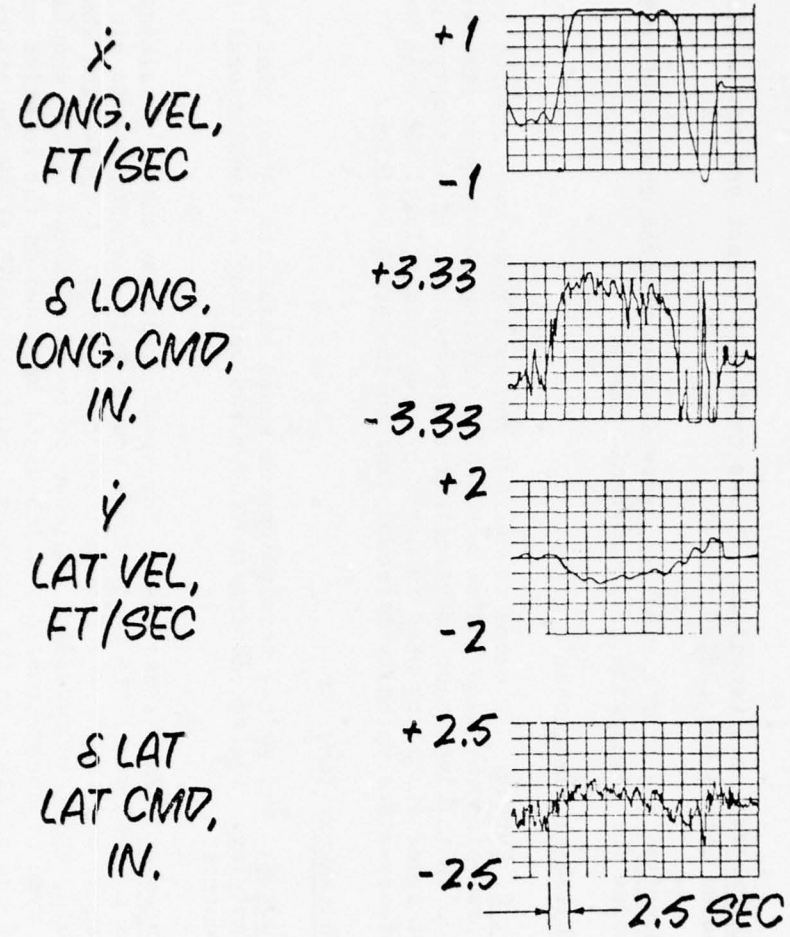


FIGURE 8

DISCUSSION

Frank Morris: In your translation function, $1/\tau S$, what value did you use for the time constant, τ ?

Whitaker: The velocity response, as was shown upon the simulator, incorporated a value for τ that was a little larger than a second.

Morris: You mentioned "severe turbulence". What magnitudes and what kind of transfer functions did you use to describe the gust input into the vehicle.

Whitaker: As I recollect, it was typically 6 feet per second white noise into a one radian filter.

Morris: You didn't simulate gusts in your program them, and instead used noise for simulation of aerodynamic gusts?

Whitaker: Yes, that's right.

H. C. Curtis: It seems to me that you have to be very careful with your terminology because you're not really talking about speed stability. You're talking about longitudinal force control. A helicopter has plenty of speed stability when in hover by your terminology. It does have a steady-state velocity corresponding to its stick position.

Whitaker: Yes.

Curtis: And so the terminology of speed stability is not what you're implying. You're closing two loops and getting a translational force control.

Whitaker: In a sense, yes. The speed stability that I'm talking about is a speed stability that allows you to trim the airplane in air turbulence, and that's the reason I use those words. I agree with what you said, and I am extending the concept to say that we really should supply a type of speed stability which would be based on the relative velocity of the airplane to its touchdown point and would allow the pilot to trim with respect to the touchdown point. That's different from the speed stability associated with airspeed in the case of helicopters where it takes a force gradient to produce a velocity change. If you disturb a helicopter with a pulse, it won't return to its initial speed in a trim sense.

Curtis: But it would if it had stable dynamics. It wouldn't return if the dynamics were unstable.

Whitaker: It'll tend to, but it won't do so in a time that's critical to the pilot in the task he's doing. If you're up at a 1000 feet where the pilot can let the airplane move large distances to let the speed settle out, then I agree with you. But the distance that's critical to the pilot as he approaches the ground, it won't happen fast enough.

Curtis: But that's a dynamic stability problem. As I said, the terminology here is confusing to me. It's not a static stability problem.

Whitaker: It's not?

Curtis: It's a dynamic response. You have plenty of static speed stability if you just talk about the words "speed stability".

Whitaker: Yes, in a sense if you analyze the system, many of these V/STOL aircraft are statically stable at hover. All we're really saying is that the aerodynamic forces associated with that static stability takes such a long time period to act that it won't provide any useful stability to the pilot in his task of hovering close to the ground.

Curtis: That's a dynamic stability problem.

Whitaker: That's right. That's essentially what I'm trying to say.

Duane McRuer: What would your definition of an inexperienced pilot be in contrast to an experienced pilot?

Whitaker: Experienced pilots have 8000 hours in a helicopter and have flown all kinds of helicopters from small to the largest. The inexperienced pilot was a private pilot who was basically an engineer and had quite a bit of time flying engineering simulators, but he was just a private pilot.

McRuer: Not rated in a helicopter?

Whitaker: Not rated in helicopters and not a military pilot. He could fly the velocity control system in the hover mode with very minimal training when in smooth air without turbulence. In turbulence, he could do the task quite well with training.

Irving Ashkenas: I think you kind of loaded the dice in favor of your velocity control system because your rated command system really amounted to a K over S^2 in the outer loop, and we've all been through that. We know that K over S^2 is not very good. So I think that you really missed the boat. You should have gone into the attitude control vs. the outer loop velocity command system. That would have been a good experiment.

Whitaker: I agree that with that control system, the performance would have been better. You wouldn't have a system which was trimmable with respect to the landing point, and you wouldn't have a system that was a velocity command system with respect to the landing point. That is what we think critically unloads the pilot.

Ashkenas: Well, you're talking about the perturbations due to wind gusts. But it's just like driving a car in a wind gust. You have your lateral speed response that is perturbed by the gusts, and it isn't all that difficult to control as long as you have your K over S term in the outer loop. That's relatively easy task for even an enexperienced operator to perform. We've got lots of data to show us that.

Mike Eden: What worries me about velocity systems that use attitude in order to achieve a translational velocity is how far a pilot might like to slave attitude close to a ground ring where he might hit a wheel or something, or just generally hit obstructions around the deck. Doesn't direct control over attitude disappear when using that type of rate system? I've been wondering about that principle with systems that employ attitude as against, say, direct vectoring of thrust.

Whitaker: Direct vectoring of the thrust allows you to control attitude independently. I wouldn't argue that this is an improvement from the pilot's point of view. For conditions where the pilot is trying to sense cues such as at night with poor vivibility, that may be an important task. It wasn't something we were able within our experiment to address here, so I have nothing I can contribute directly to that.

Dave Green: The work that was done by Sperry Flight Systems, Bob Buffum (NATC) has all the background that I know, flew in an aircraft and a number of aircraft were mechanized. I think the speed stability thing came out to show the biggest variation in pilot desires that has ever shown up in flight system work. You have one pilot who would be willing to ride through 30 degrees attitude changes to achieve "I want to go from here to there immediately or yesterday" and other people who would absolutely not stand still for that. I think that was one of the big things that came out of that whole program. Considerable work was done in this area that would be useful to go back and look at, in my opinion. I think the Army sponsored a lot of the work.

Whitaker: Yes, I think the Army studies kind of support the idea that velocity (control) is a useful and desireable feature.

Green: I think the only difference in the Navy line is that they were looking at the very same task that you were talking about; i.e., coming alongside a destroyer, stopping and then closing up quickly. This requires making a precision adjustment when coming aboard. That's what is somewhat different from what the Army was doing, in my opinion.

Anon: I just have a quick question. Was your target fixed or moving during your experiments?

Whitaker: The data I showed you was for a fixed target. The task was loaded by the air turbulence which meant that he was riding a moving base. We would like to do the experiment with a moving target, where the task of landing on a moving deck would involve sensing the relative motions. That's not within the investigative capability of our particular simulator at this time.

Jim Davis: I'd just like to mention that with regard to a pitching deck, the U.S. Army has gone through a significant amount of development work in this type of control system which we call "relative ground speed control" for both the Tactical Air Guidance (TAG) program in the C-47 and now the Boeing 347 where you have a helicopter fly-by-wire development program. There's a substantial amount of simulation work in the different types of control systems based upon response characteristics all the way through to the actual play article. Certainly the claims formvelocity control systems such as their reduced gust sensitivity, preciseness of control and significant reduction of work load have been verified by this program. I think the technology is here to implement that kind of a program using that kind of a control system in almost any kind of a vehicle. The thing which remains is the cost reduction of some type of an adequate sensing system to provide the relative ground speed signals. We haven't obtained that yet. We used inertial systems on both the TAG and the HLH programs. The Navy search and rescue helicopters had similar speed input using a Doppler approach.

Ashkenas: I'd just like to comment on that last remark. I don't think it was quite true that the only thing remaining was the physical hardware because I think, in the final epilogue, the Army had to change the stick force characteristic of the manipulator in order to give the pilot some more sense of feeling. That is, he had lost his intermediate loop control and wasn't able to get the proper motion harmony between attitude and velocity without some additional cues in the stick. So this business of using attitude as an inner loop, I think, is still pretty important to the pilot. We should not forget the whole idea of motion harmony. How does the pilot really fly? He's not interested in seeing velocity if it involves large perturbations in attitude, and that's the point that Dave Green was making. I think that we've got to remember that.

Davis: Can I make one rebuttal to that? What you are talking about was the concept we had for the TAG aircraft; namely, a very strong viscous force controller. Now that whole concept was reworked for the HLH program where we did indeed maintain the proper relationship fom the attitude or brake response to a control input.

V-STOL FLYING QUALITIES REQUIREMENTS IN THE UK

JOHN R WILLIAMS

AEROPLANE AND ARMAMENT EXPERIMENTAL ESTABLISHMENT
BOSCOMBE DOWN

1 The evolution of V-STOL Flying Qualities Requirements is a lengthy process and until it has been achieved in the UK qualitative assessments of suitability provide the essential demonstration of acceptability. Past experience during acceptance and suitability testing has, however, shown that acceptance based purely on pilot qualitative assessment can be problematic as a result of variabilities in pilot opinion, background and recent experience.

The Aeroplane and Armament Experimental Establishment at Boscombe Down (A&AEE) is the official UK military aeroplane acceptance and assessment agency and its experience is, therefore, limited in general to military aircraft which have been procured for the armed services. Thus apart from helicopters, (which the author is not qualified to discuss) current UK interest in the V-STOL field centres around the Harrier and Sea Harrier.

During recent V-STOL suitability testing at the A&AEE attempts have been made to provide a numerical basis for assessments of suitability. As time goes by it is hoped that the more quantitative assessments being made, together with measured aircraft characteristics, will assist in the formulation of requirements and criteria.

The process currently being used at the A&AEE is probably best illustrated by using as an example some intensive assessments of the Harrier handling qualities during the STO manoeuvre and subsequent semi-jetborne flight.

2 ASSESSMENT OF HARRIER HANDLING QUALITIES DURING STO AND SEMI-JETBORNE FLIGHT

2.1 BACKGROUND In 1972 the Harrier GR1 was converted to GR3 standard by installation of the improved Pegasus 11 engine. The modification was viewed purely as an engine change - no changes in handling qualities were expected and following a brief engine handling assessment the aircraft entered service with the Royal Air Force.

Subsequently a number of incidents were reported which cast doubt on the longitudinal controllability of the aircraft during excursions to high ADD in semi-jetborne flight at high power settings. These incidents led to an intensive investigation by the contractor into

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the handling qualities of the aircraft during the STO for all authorised store combinations and loadings. As a result of these trials an aft c of g limit, more restrictive than the existing one, was proposed for maximum performance STOs and A&AEE undertook a limited trial to assess this limit. During two sorties, one forward, one aft of the proposed limit the assessment pilot was obliged to "nozzle out" (reduce nozzle angle) of each take-off, having decided that response to stick alone was inadequate.

In the absence of applicable requirements, the subsequent discussions with the Contractor concerning the problem were rather unproductive, as the whole argument was based on qualitative assessment with all the associated difficulties relating to variabilities of skill, experience, opinion and recent practice. This conflict of qualitative opinion was beyond resolution in a rational technical manner. Therefore, when the A&AEE was later tasked with assessing a new technique for STOs, proposed by the contractor, the Establishment considered it necessary to devise a suitable set of quantitative rules to assist in the assessment.

2.2 APPLICABILITY OF EXISTING REQUIREMENTS A search of existing literature on V-STOL requirements produced the information shown in Figure 1. The information is extracted from AP 970, AGARD 577 and MILSPEC 83300 and Harrier characteristics during the STO phase are compared with the requirements.

It can be seen that the degree of instability of the Harrier in this phase of flight contravenes all requirements, whilst the aircraft does meet the control power/sensitivity requirements of AGARD 577 for all the configurations tested. In addition, stability was not measurably variable with c of g. It became apparent, therefore, that current requirements were of little assistance in this case and that a rating system would have to be devised specifically for assessing the STO manoeuvre in the Harrier. The assessment scheme, outlined below, was devised by Squadron Leader R Pengelly, the Harrier Project Pilot at A&AEE.

2.3 ASSESSMENT SCHEME FOR STO HANDLING QUALITIES The assessment scheme detailed required levels of accuracy for performance of the STO manoeuvre and combined these with assessment of pilot compensation to produce a rating on a Cooper-Harper scale.

Figure 2 defines the task, and the minimum levels of accuracy required for desirable and adequate performance of the pilot-aircraft system. Figure 3 presents the familiar Cooper-Harper pilot rating scale which was used to input pilot effort or compensation.

It was appreciated that some margin of control should be available to counter upsets and, as can be seen from Figure 2, this was integrated somewhat with the accuracy achieved. If the margin were eroded in producing the higher level of performance then the rating did not suffer as much as it would otherwise.

It may be of interest to examine briefly the logic which resulted in the definitions for the levels of system performance:-

a As the maximum performance STO is used primarily for obstacle clearance from limited strip operation, it was considered essential from a flight safety standpoint that performance was not significantly eroded. It was on this basis that it was decided to require that it be possible to prevent ADD reducing by more than 1 unit from the target value of 12.

b The upper levels of +1 and +2 units were specified to maintain a "desirable" margin of 2 units and an adequate margin of 1 unit below the current "never exceed" value of 15 units ADD.

c The 9^{o} tailplane angle limit for maximum control usage was arbitrarily chosen to preserve one third of the reaction control power remaining beyond trim value for control of upsets.

d Finally and obviously any necessity to reduce nozzle angle for control of ADD excursions was classed as a loss of control for a given configuration and was awarded a rating of 10.

2.4 ASSESSMENT OF NEW TECHNIQUE The new STO technique proposed by the contractor was basically a restriction in STO nozzle angle to a maximum of 50^{o}. Thus, in the characteristic ambient conditions experienced in Europe, this meant that STOs at maximum weight with outboard stores and an aft c of g were flown with 50^{o} nozzle angle instead of the 60^{o} value specified by the Flight Manual.

The assessment programme included some STOs using the original Flight Manual technique to permit a direct comparison and to give the Establishment a second opportunity to assess the existing technique using the new rating scheme.

Figure 4 displays the pilot ratings given for the different configurations and techniques. The ratings indicate clearly that:-

a Use of the new technique improved significantly the handling qualities during STOs with outboard stores.

b Use of this assessment system resulting in ratings in excess of 8 resolved clearly the original argument over the acceptability of the outboard stores configuration using the original Flight Manual technique.

The new technique, a considerable improvement, resulted in the most critical Harrier configuration being acceptable for maximum performance STOs.

2.5 DEVELOPMENT OF CRITERIA In the normal course of events the task of the assessment agency would be complete at this point. However, the results of this land based work had led to some doubt as to the acceptability of the observed Harrier handling qualities for the apparently more critical shipboard launch manoeuvre. Changes in centre of gravity and aerodynamic control are proposed for the Sea Harrier but no estimates were available as to the effects of these. The A&AEE felt that some guidance was necessary on the level of handling qualities required and therefore undertook to examine more closely the data obtained during the STO assessment. Examination of relevant aircraft characteristics, static stability, control sensitivity and control power indicated that a correlation existed between pilot rating and control power.

Figure 5 shows the effect of the new technique on control power and Figures 6 and 7 demonstrate the measured correlation between control power and pilot ratings. In this context it is worth mentioning two points that have emerged during subsequent trials.

a During shipboard trials with the GR3 aircraft for which an assessment scheme was not devised, a pilot qualitative assessment rated the aircraft as having the minimum level of acceptable handling qualities. When control power data for this aircraft is superimposed on the criteria developed during land based work (Figure 7) it implies a rating of 6!!!

b It is interesting to note that a similar correlation appears in the Background Information to MILSPEC 83300, but doubts are expressed regarding the apparent lack of reference to the effects of control usage.

Recent STO assessments on the two seat Harrier have provided interesting information on this aspect. In a series of assessment flights two pilots employed the previously discussed rating scheme. Subsequent analysis showed that both achieved the same accuracy of ADD control (Figure 8) and both awarded similar ratings (Figure 8) on the basis of workload or compensation. The ratings given were in complete agreement with the criteria developed on the single seat GR3. However, the techniques used by the two pilots were significantly different as shown in Figure 9. One pilot, in general, used higher gain and higher frequency control inputs, his measured control usage being twice that of the other.

Thus these two pilots achieved the same results, awarded the same ratings, which correlated well with control power remaining, though one used significantly more of this control power than the other.

2.6 USE OF DATA IN FORMULATION OF REQUIREMENTS

2.6.1 LAND BASED STOs As a result of the assessments of STOs in the Harrier aircraft, and the correlations obtained between pilot rating and control power, the possible criteria for STO and semi-jetborne flight shown in Figure 10 have emerged. These are based on the flight safety implications of:-

a Achieving the planned performance specified in the Flight Manual by the ability to maintain crucial parameters specified in the technique within certain limits.

b Maintaining a safe margin from specified "never exceed" limits of parameters which could result in loss of control.

c Ensuring that at the maximum permissible values of flight safety orientated parameters, control margins exist which have been found to be adequate.

d An ability to achieve desired or adequate levels of aircraft-pilot system performance without recourse to exceptional pilot skill or greater than moderate pilot compensation.

The above statements might almost be considered the general set of requirements corresponding to the specific Harrier criteria of Figure 10. They are in fact the logic behind the specific criteria and were much easier to specify retrospectively.

2.6.2 SHIPBOARD LAUNCH Figure 11 shows a set of criteria prepared for a recent shipboard assessment of a Harrier modified to possess the predicted Sea Harrier control power and centre of gravity. Again it must be emphasised that they have no contractual basis and were prepared purely as a tool to assist in assessing launches which would otherwise have been judged in a purely qualitative manner.

As could be expected the logic behind these criteria is, in general, similar to that outlined in the preceding section on land based STOs with the following additions:-

a ITEM 5 To cover variability in launch dynamics resulting from variable tailplane movement during the deck run.

b ITEM 6 To ensure safety with a reasonable degree of error in initial trim setting.

c ITEM 8 To legislate for a change in technique to use of pitch attitude as a primary flight control cue.

d ITEM 9 To cater for despatch operations with known system failures such as auto-stabilisers or HUD.

It is worthwhile noting that the requirements again proved valuable in assessing a failure case which resulted in conflicting pilot opinion on acceptability.

In general, for failures such as auto-stabiliser and HUD, two cases need consideration:-

a The despatch case with a known unserviceability.

b The failure during the launch manoeuvre.

For the former it is possible to impose limitations which ensure safety at a reduced level of flight control accuracy. Item 9 in the above requirements implies this.

For the second type of failure, judgement must depend to a large degree on the statistical probability of the occurrence during the very short critical period of time between system checkout and post transition or safe altitude. If the probability is unacceptably high then it would be necessary to demonstrate only flight safety at the minimum authorised launch speed, using the specified Flight Manual technique but allowing for stores jettison, tripping of limiters and use of water to provide additional margins.

3 CONCLUSIONS Though currently the UK has no general military V-STOL requirements, machinery is now moving which will, hopefully, result in some requirements in approximately three years. In the meantime, with five years of suitability testing ahead the A&AEE is undertaking the simpler task of devising criteria specific to the Harrier as tools for quantitative assessment.

It is hoped that this work will contribute to the official effort in the following ways:-

a Providing quantitative assessments which will permit correlation with aircraft characteristics to produce design criteria.

b Providing an expertise and background knowledge of those aspects demanding attention if requirements are to be comprehensive and experience in the application of such requirements.

c Providing a large number of criteria which, although specific to the Harrier, should assist in the manner indicated in Section 2.6.1 in the more difficult task of formulating general requirements.

It is considered above all that the final requirements should be viewed as assistance and guidance to all concerned not as a set of rules which would restrict the contractor. They should be prepared in consultation with the contractor so that they can reflect his experience and "know how" and so that they can be accepted by him as being sensible and soundly based. Finally they should be flexible, always open to discussion and applied intelligently to ensure that their spirit rather than their letter is observed.

ACKNOWLEDGEMENTS

Acknowledgements are due to Harrier Project contribution to the work underlying this paper. The author would also like to thank Mrs R Sandford for assistance in the preparation of this paper.

NOTE: The opinions expressed in this paper are those of the author and do not necessarily reflect those of the Aeroplane and Armament Experimental Establishment.

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1	Anon	V-STOL Handling, Parts 1 and 2. AGARD Report R-577.
2	Anon	Military Specification - Flying Qualities of Piloted V-STOL Aircraft - MIL-F-83300.
3	Anon	Design Requirements for Service Aircraft - Aviation Publication AvP 970.
4	Cooper G E, Harper R P Jr (Cornell Aeronautical Labs)	The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities. National Aeronautics and Space Administration, Ames Research Centre. Technical Note D-5153. April 1969.

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FIGURE 1A

MILSPEC 83300 REQUIREMENTS COMPARED WITH HARRIER CHARACTERISTICS

REF	ITEM	HARRIER CHARACTERISTICS
3.3	FORWARD FLIGHT : SPEED RANGE 35 KN TO V_{CON}	
3.3.1	LONGITUDINAL EQUILIBRIUM	
	Level 1 Variation of control position with pitch attitude and airspeed shall be stable or neutral.	Unstable with respect to speed and ADD.
	Level 3 (2VFR) Control position instability shall not exceed $\frac{1}{2}$" over range of instability.	1" control movement instability between 8 and 15 ADD.
3.3.2	DYNAMIC RESPONSE	
	Level 1 Response shall not be divergent.	Time to double amplitude SAS off <5 secs.
	Level 2 Time to double amplitude >12 secs.	No data available with SAS on.
	Level 3 Time to double amplitude >5 secs.	
3.3.4	STABILITY IN MANOEUVRING FLIGHT Aft movement of control to maintain increase in ADD.	Aircraft unstable with respect to ADD.
3.3.5.1	MANOEUVRING CONTROL MARGINS At least 50% of nominal control moment available to pilot in critical direction.	
3.6	TAKE-OFF	
3.6.1	PITCH CONTROL EFFECTIVENESS IN TAKE-OFF Shall not restrict the take-off performance and shall be sufficient to prevent over-rotation to undesirable attitudes.	

FIGURE 1B

AGARD 577 REQUIREMENTS COMPARED WITH HARRIER CHARACTERISTICS

REF	ITEM	HARRIER CHARACTERISTICS
2.2	PITCH CONTROL POWER Minimum required for manoeuvre .05/ 0.2 rads/sec^2.	
2.3	CONTROL SENSITIVITY No values given for STOL with acceleration control. Minimum value for rate control .08 - .12 rads/sec^2/in.	Characteristic value for Harrier during STO 0.15 rads/sec^2/ in.
2.4	PITCH DAMPING For rate system not more than 1 control reversal to stabilise on selected attitude.	SAS off aircraft divergent time to double amplitude calculated to be <2 secs. Aircraft has no short period oscillatory modes with SAS on.
2.8	DYNAMIC STABILITY Response of aircraft should not be divergent. Damping of short period oscillation must be greater than 0.3.	Response still basically apperiodic. Constant operation of control required to hold attitude.
2.9	LONGITUDINAL CONTROL IN TAKE-OFF Effectiveness should not restrict take-off performance for STOL. Adequate control margins and sufficient pitch damping should exist to prevent over-rotation to undesirable attitudes.	

FIGURE 1C

AP 970 REQUIREMENTS COMPARED WITH HARRIER CHARACTERISTICS

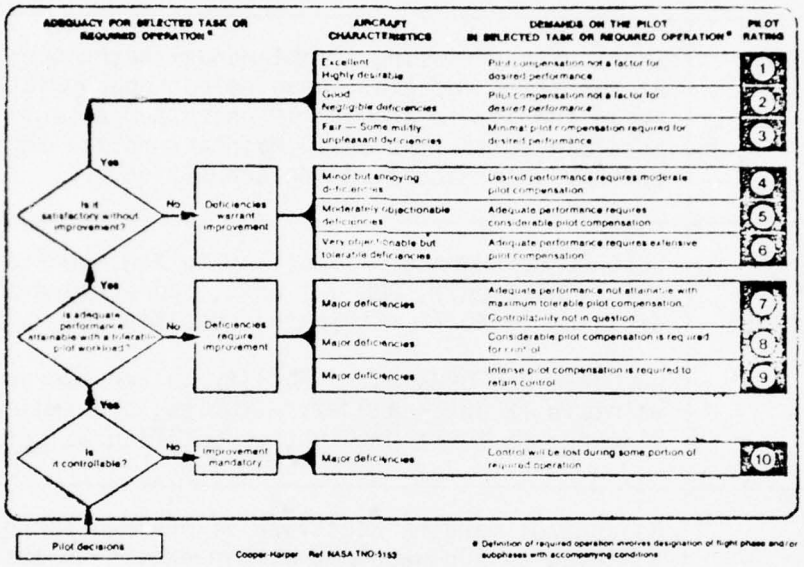
REF	ITEM	HARRIER CHARACTERISTICS
CH 601 Para 2	The aeroplane shall be positively stable . . . The aeroplane shall be stable with respect to incidence.	Aircraft statically unstable.
Para 3	Short period oscillation requirements for damping.	No periodic response.

FIGURE 2

ASSESSMENT CRITERIA FOR STO

ITEM	REQUIREMENT
SELECTED TASK	Short take-off using flight manual technique. At specified rotation speed select appropriate nozzle angle and aim to acquire 12 units ADD as soon as possible after lift off. Maintain nozzle angle and ADD until accelerating transition.
LEVELS OF SYSTEM PERFORMANCE	DESIRED PERFORMANCE Ability to achieve and maintain 12 units ADD ± 1 unit, and achieve a distance to 50 ft within the specified 3σ value. ADEQUATE PERFORMANCE Ability to achieve and maintain 12 units ADD +2, -1 units, and achieve a distance to 50 ft within the specified 3σ value.
CONTROL MARGIN	No control margins specified if desired performance achieved as adequate ADD margin exists to absorb upset. Adequate performance must not require the use of more than +9 tailplane.
PILOT COMPENSATION	Qualitative assessment of compensation to combine with system performance for use with Cooper-Harper scale (Figure 3).

FIG. 3.



DEFINITIONS FROM TN D-5153

COMPENSATION

The measure of additional pilot effort and attention required to maintain a given level of performance in the face of deficient vehicle characteristics.

HANDLING QUALITIES

Those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role.

MISSION

The composite of pilot-vehicle functions that must be performed to fulfill operational requirements. May be specified for a role, complete flight, flight phase, or flight subphase.

PERFORMANCE

The precision of control with respect to aircraft movement that a pilot is able to achieve in performing a task. (Pilot-vehicle performance is a measure of handling performance. Pilot performance is a measure of the manner or efficiency with which a pilot moves the principal controls in performing a task.)

ROLE

The function or purpose that defines the primary use of an aircraft.

TASK

The actual work assigned a pilot to be performed in completion of or as representative of a designated flight segment.

WORKLOAD

The integrated physical and mental effort required to perform a specified piloting task.

HANDLING QUALITIES RATING SCALE.

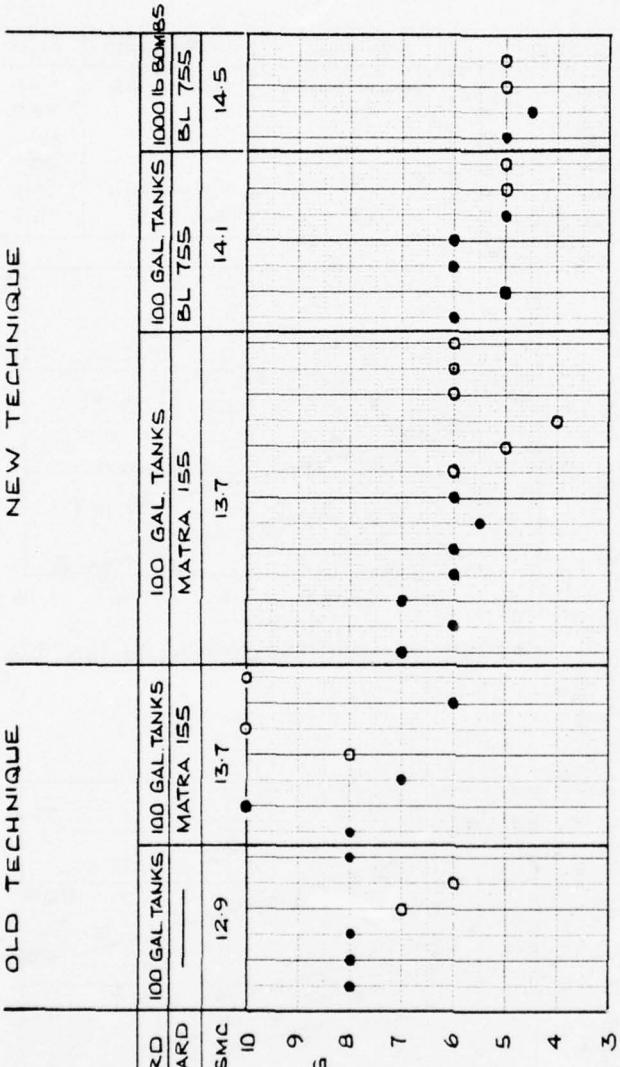
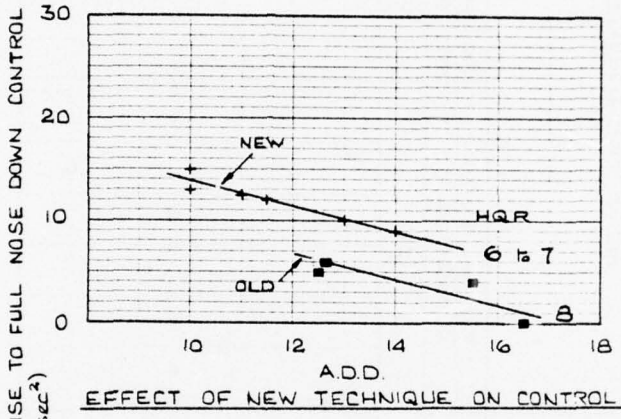


FIG. 4

EFFECT OF S.T.O. TECHNIQUE ON PILOT RATING.

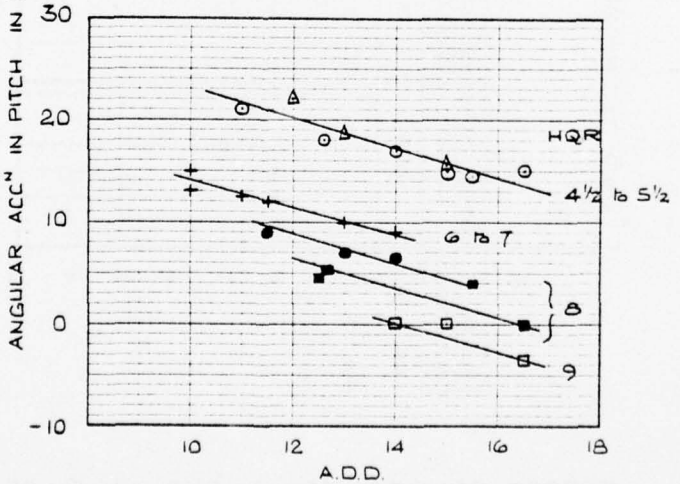
FIG. 5

TECHNIQUE		INBOARD	OUTBOARD	FLAP
NEW	+	100 GAL. TANKS	MATRA 155	YES
OLD	■	↓	↓	YES
OLD	□			NO
NEW	△			NO
OLD	●		—	YES
NEW (T4)	○		BL 755	YES



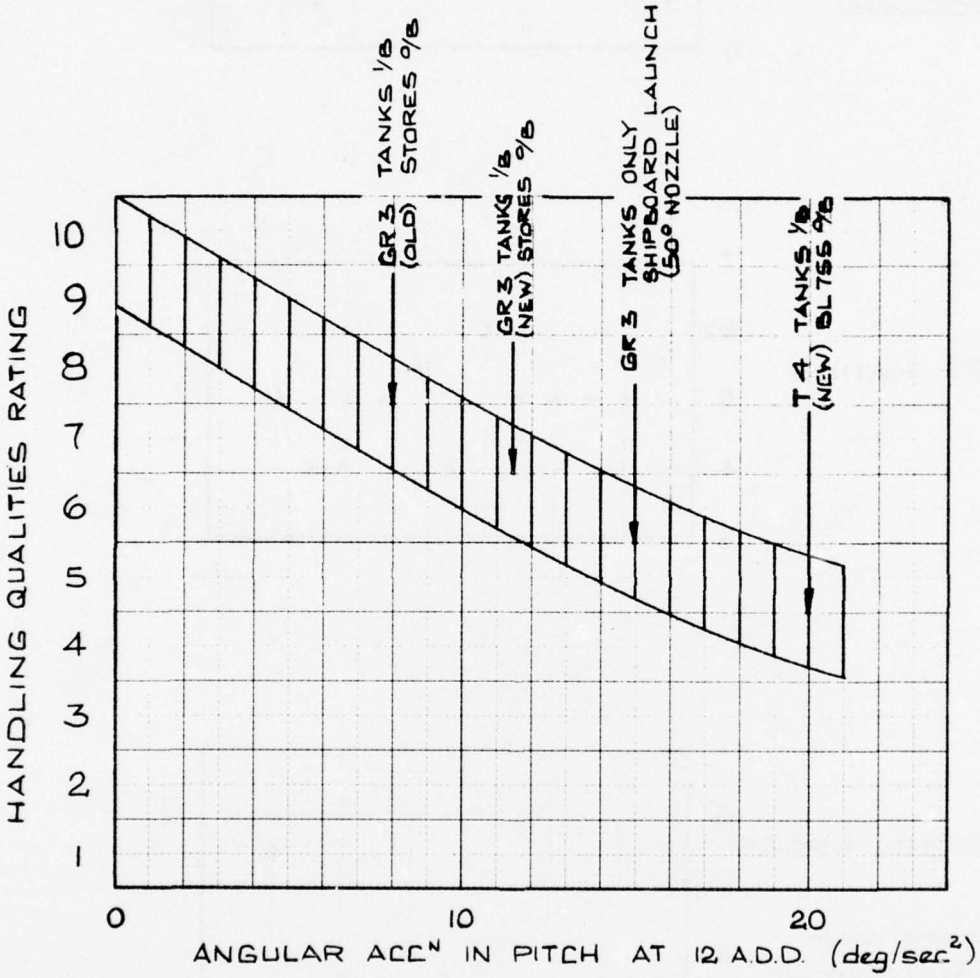
EFFECT OF NEW TECHNIQUE ON CONTROL POWER

FIG. 6



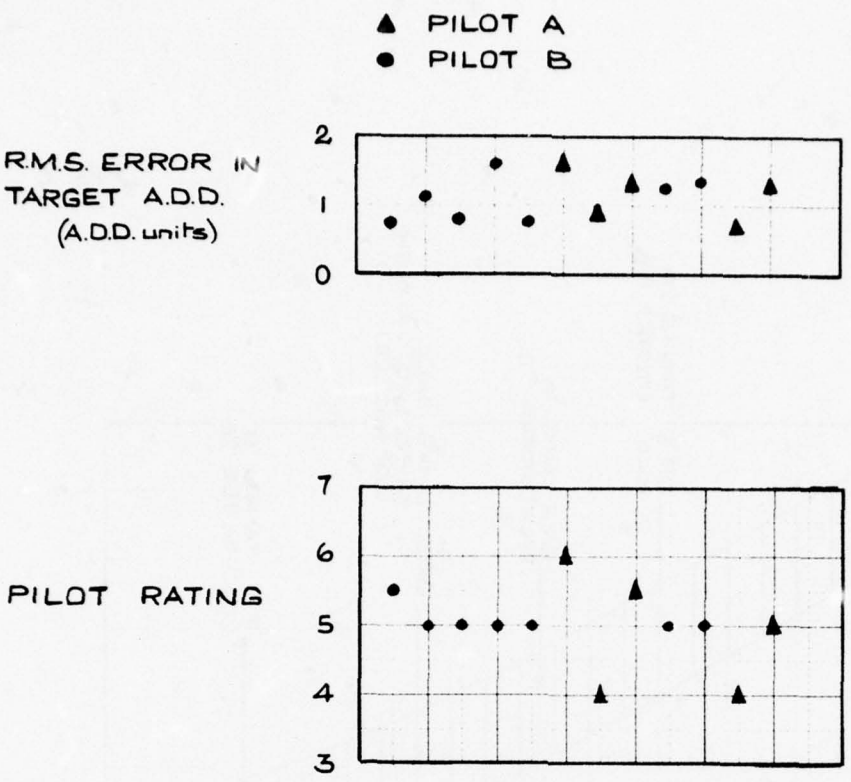
CORRELATION BETWEEN CONTROL POWER AND HANDLING QUALITIES RATING (H.Q.R)

FIG. 7



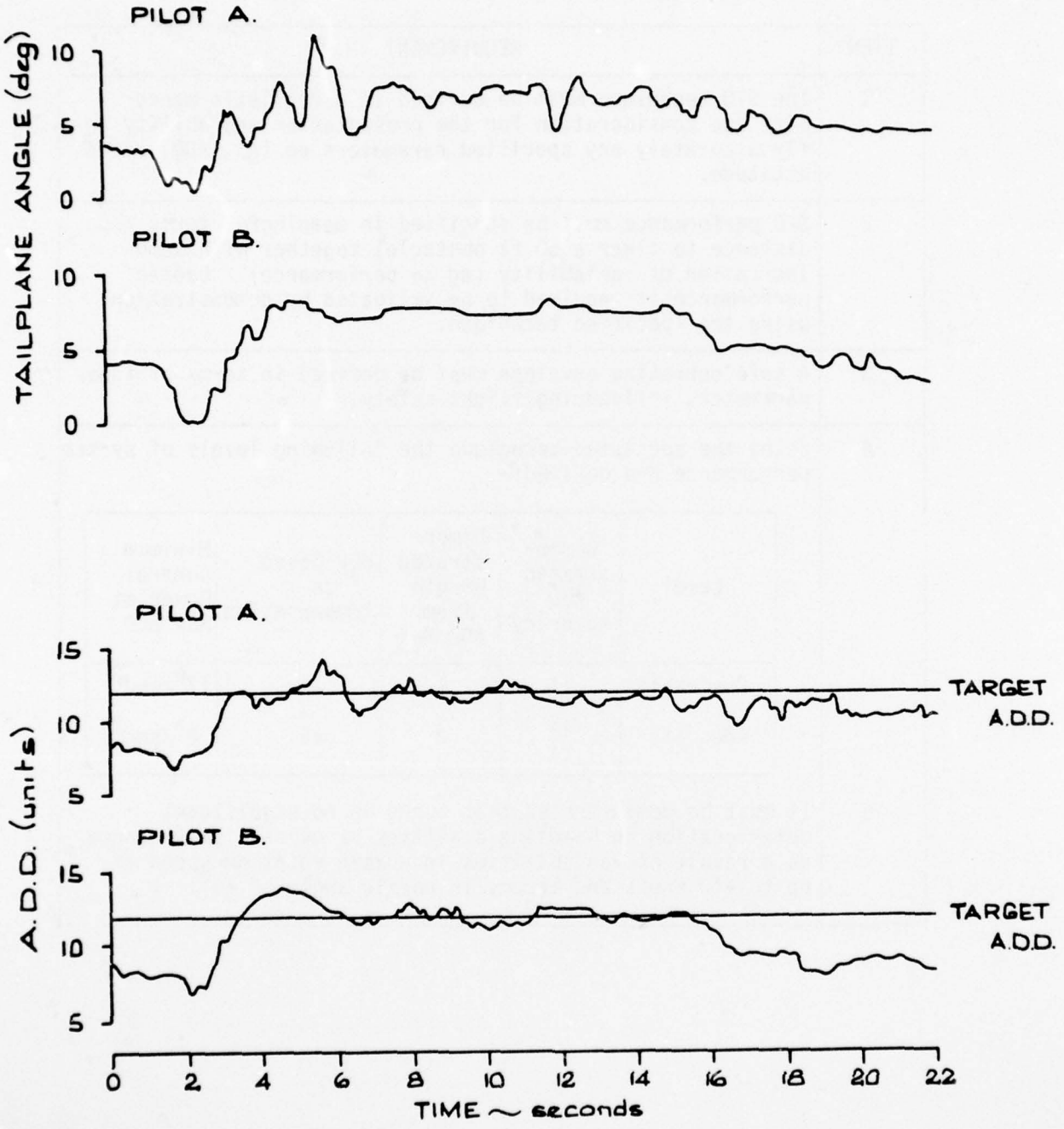
HANDLING QUALITIES CRITERIA FOR S.T.O. AND SEMI-JETBORNE FLIGHT.

FIG. 8



INFLUENCE OF CONTROL USAGE ON PILOT RATING AND SYSTEM PERFORMANCE FOR TWO PILOTS.

FIG. 9



COMPARISON OF CONTROL USAGE AND SYSTEM PERFORMANCE FOR TWO PILOTS.

FIGURE 10

POSSIBLE STO REQUIREMENTS FOR HARRIER

<table>
<tr><th>ITEM</th><th>REQUIREMENT</th></tr>
<tr><td>1</td><td>The STO technique must be defined in a realistic manner with due consideration for the presentation and ability to fly accurately any specified parameters eg IAS, ADD, pitch attitude.</td></tr>
<tr><td>2</td><td>STO performance must be specified in meaningful terms (eg distance to clear a 50 ft obstacle) together with some indication of variability (eg 3σ performance). Quoted performance is required to be validated by demonstration using the specified technique.</td></tr>
<tr><td>3</td><td>A safe operating envelope must be defined in terms of those parameters influencing flight safety.</td></tr>
<tr><td>4</td><td>Using the specified technique the following levels of system performance are defined:-
<table>
<tr><th>Level</th><th>Demonstrated ADD Accuracy</th><th>Demonstrated Margin from ADD Max</th><th>HQR Based on Compensation</th><th>Minimum Control Power at Max ADD</th></tr>
<tr><td>Desirable</td><td>± 1</td><td>1</td><td>≤ 4</td><td>$17^{o}/sec^{2}$</td></tr>
<tr><td>Adequate</td><td>$^{+2}_{-1}$</td><td>2</td><td>≤ 6</td><td>$8^{o}/sec^{2}$</td></tr>
</table></td></tr>
<tr><td>5</td><td>It must be demonstrated that there is no significant deterioration in handling qualities or overall performance as a result of variabilities in nozzle rotation speed of up to ± 10 knots and errors in nozzle angle of $\pm 5^{o}$.</td></tr>
</table>

FIGURE 11

POSSIBLE SHIPBOARD LAUNCH REQUIREMENTS FOR HARRIER

<table>
<tr><th>ITEM</th><th>REQUIREMENT</th><th>JUSTIFICATION OR BASIS</th></tr>
<tr><td>1</td><td>The launch technique, including trim setting shall be defined in a realistic manner with due consideration for the presentation of and the ability to fly accurately specified parameters eg IAS, ADD, pitch attitude.</td><td>Need for consistent and repeatable profile for performance definition.</td></tr>
<tr><td>2</td><td>Launch performance shall be specified in terms of end speed and sink and must be demonstrated to be achievable using the specified technique.</td><td>Planning and Safety implications.</td></tr>
<tr><td>3</td><td>A safe operating envelope must be defined in terms of those parameters influencing flight safety.</td><td></td></tr>
<tr><td>4</td><td>Where performance data is based on simulation, rotation must be demonstrated to be achievable within the time assumed by the simulation and initial ADD achieved must not be less than the target value - 1 unit.</td><td>Check of practicality of technique and interaction of performance and handling qualities.</td></tr>
<tr><td>5</td><td>For the specified trim setting $+2\sigma$ of the measured deck end variation in tailplane angle, the following levels of pilot-aircraft system performance are defined.
<table>
<tr><th>Level</th><th>Demonstrated ADD Accuracy</th><th>Demonstrated Margin From ADD Max</th><th>HQR Based on Compensation</th><th>Minimum Control Power at ADD Max</th></tr>
<tr><td>Desirable</td><td>± 1</td><td>1</td><td>≤ 4</td><td>$17^{o}/sec^{2}$</td></tr>
<tr><td>Adequate</td><td>$^{+2}_{-1}$</td><td>2</td><td>≤ 6</td><td>$12^{o}/sec^{2}$</td></tr>
</table>
</td><td>-1 ADD accuracy required to preserve performance. Reduced ADD margin permitted for aircraft exhibiting tighter ADD control</td></tr>
</table>

FIGURE 11
CONTD

ITEM	REQUIREMENT	JUSTIFICATION OR BASIS
6	For the specified trim setting $+2\sigma$ variation of measured variation in deck end value $+0.5^{0}$ it must be demonstrated using the specified technique that at minimum authorised launch speed the operating envelope is not exceeded.	Flight safety check on mis-trimmed case reflecting accuracy of trimming.
7	It must be demonstrated that following nozzle rotation a minimum longitudinal acceleration of .06 g is maintained.	Pilot opinion.
8	If attitude is used as a primary cue it must be demonstrated that in the maximum performance launch the implications of item 5 are met. Target ADD values should then be interpreted as the ADD values assumed for launch performance.	
9	If operations are to be permitted without a major flight control system such as HUD or SAS, then it must be demonstrated that at 10 knots below the minimum performance level authorised for such operation and using any special techniques specified, no sink occurs and the aircraft does not depart from the safe operating envelope.	Despatch cases with failed systems.

DISCUSSION

Bob Flynn: Can I conclude that you share Mr. Lacey's rather casual attitude toward unstable roots?

Williams: No, you cannot, sir. We find that in many tasks, the Harrier is very close to being unacceptable. It's barely acceptable and we'd like to see considerable improvements. But this is the airplane we have; this is the airplane the services are flying and we have to apply our requirements in a sensible sort of way. It wouldn't be quite sensible for us to say that this airplane is unacceptable. This is what we feel.

Seth Anderson: John, I wasn't quite clear on your new technique and your old technique. I missed the point or missed your explanation of what the difference was.

Williams: The difference is that the old technique specifies a changing nozzle schedule that varies with thrust/weight. So for various thrust/weight ratios you use different nozzle angles for the STO. At these high weight configurations in the U.K. environment, we'd be using something like 60° nozzle angles and I believe you still do here. So now we've gone to using 50° nozzle angles for all STO's.

Dave Ellis: *Do you specifically consider different levels of atmospheric* disturbances?

Williams: No, we have not done that. What we have done is to accept that we need certain margins to cater for the upset case. Now we have no specific evidence to make a rational assessment of what margins we need. But based on the experiences of many STO's, it looks as though the margins that we have imposed look reasonable. I might say that the requirements that we're developing have no contractual implications at all. They're merely to assist us in assessing the airplane and they're constantly subject to revision as we go along and as we learn more.

Tom Lacey: Was the main reason for going to the 50° nozzle setting just to improve the longitudinal control margins?

Williams: Yes.

REVIEW OF U.S. NAVY VSTOL HANDLING QUALITIES REQUIREMENTS

Dale E. Hutchins
Naval Air Systems Command

The renewed interest in VSTOL aircraft for U.S. Navy Shipboard operations has surfaced some widely differing opinions about VSTOL handling qualities requirements. A major source for many of these arguments has come from USMC operational experience with the AV-8A Harrier. Clearly the Harrier does not meet many of the specification requirements advocated in MIL-F-83300. Yet the Harrier continues to do an estimable job in the Marine Corps operating environment, including ship based operations. Examination of the AV-8A data base, however, shows that flight operations in the critical VSTOL regime are conducted under VFR conditions. The inability to perform terminal area operations, particularly decelerating transitions, in IMC (Instrument Meteorological Conditions) seriously limits the all weather shipbased operating capability of the Harrier. These limitations result from pilot workload saturation while trying to perform VSTOL tasks.

Reducing pilot workload can be accomplished by improvements in aerodynamic design, flight control systems, cockpit displays and terminal area guidance systems. The existing VSTOL handling qualities specification, MIL-F-83300, identifies criteria for aerodynamic and flight control systems design which should produce significant reduction in pilot workload for VSTOL mission tasks. This specification is still untried; i.e., no airplane has been designed to, built and tested against this specification, and already some revisions are needed. Even so, recent flight test experience with the AV-8A, CL-84 and VAK-191B airplanes confirm that MIL-F-83300 is basically a good specification and is workable. If the Navy were to sign a contract tomorrow for a new VSTOL airplane, I would feel comfortable using MIL-F-83300 for the flying qualities specification requirements with changes in a few areas.

One area where MIL-F-83300 is weakest is the lack of any background information or specific requirements for shipboard operations. From Navy helicopter experience aboard small ships it is apparent that VSTOL operations aboard these same ships is going to be a challenge. Currently, during helicopter landing recoveries if the ship motion, wind or turbulence are too severe the pilot establishes a station-keeping hover just aft of the ship and waits until the ship motion or winds become more favorable. The high fuel consumption rate during hover will likely preclude this option for VSTOL airplanes. Therefore, VSTOL airplanes will have to be designed to operate in the small ship environment of deck motion, winds from nearly all azimuths, and ship generated wake turbulence.

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A look at the launch and recovery capability of the current SH-2F LAMPS MK I helicopter shows the impact of these environmental factors. Figure 1 presents the launch and recovery wind limitations for SH-2F operations aboard a CG-26 class ship. The CG-26 class ship is 524 ft long with 7714 tons displacement. By comparison the new DD963 class ship designated for multi-mission VSTOL operations is 529 ft long with 7698 tons displacement. Wind limitations shcwn in Figure 1 for the SH-2F/CG-26 combination represent the greatest operational capability identified to date. These limitations were derived from actual at-sea flight tests by the Naval Air Test Center. The boundary limits are established from instrumented test data and qualitative pilot task opinions, ala the Cooper-Harper Rating Scale. The orientation of the wind limits around the ship centerline is determined by the approach and line-up line for a particular ship; maximum winds occurring nose-on to the helicopter. The angled deck approach is required to permit a straight-ahead wave-off or missed approach flight path. Truncations of the wind limits at varying azimuths results from factors such as helicopter crosswind (more correctly omni-directional wind) capability, ship generated turbulence, and pilot visibility. Note that Figure 1 applies to day, VFR conditions.

Figure 2 now presents the wind limitations for night operations (500 ft ceiling, 1 mi visibility without Precision Approach Radar or 300 ft, 1/2 mi with PAR) for the same ship motion conditions using white deck lights for visual aids but without a glide slope indicator. With increased ship motion the wind limitations are further reduced to those presented in Figure 3 for either day operations or night operations using a glide slope indicator. The ship motion associated with Figure 3 is typical of Sea State 5 conditions for the CG 26 class ship. Experience with the SH-3 series helicopters aboard this same ship class show trends similar to those of Figures 1 through 3 except for the introduction of some minimum wind-over-deck limits to improve hot day performance capabilities.

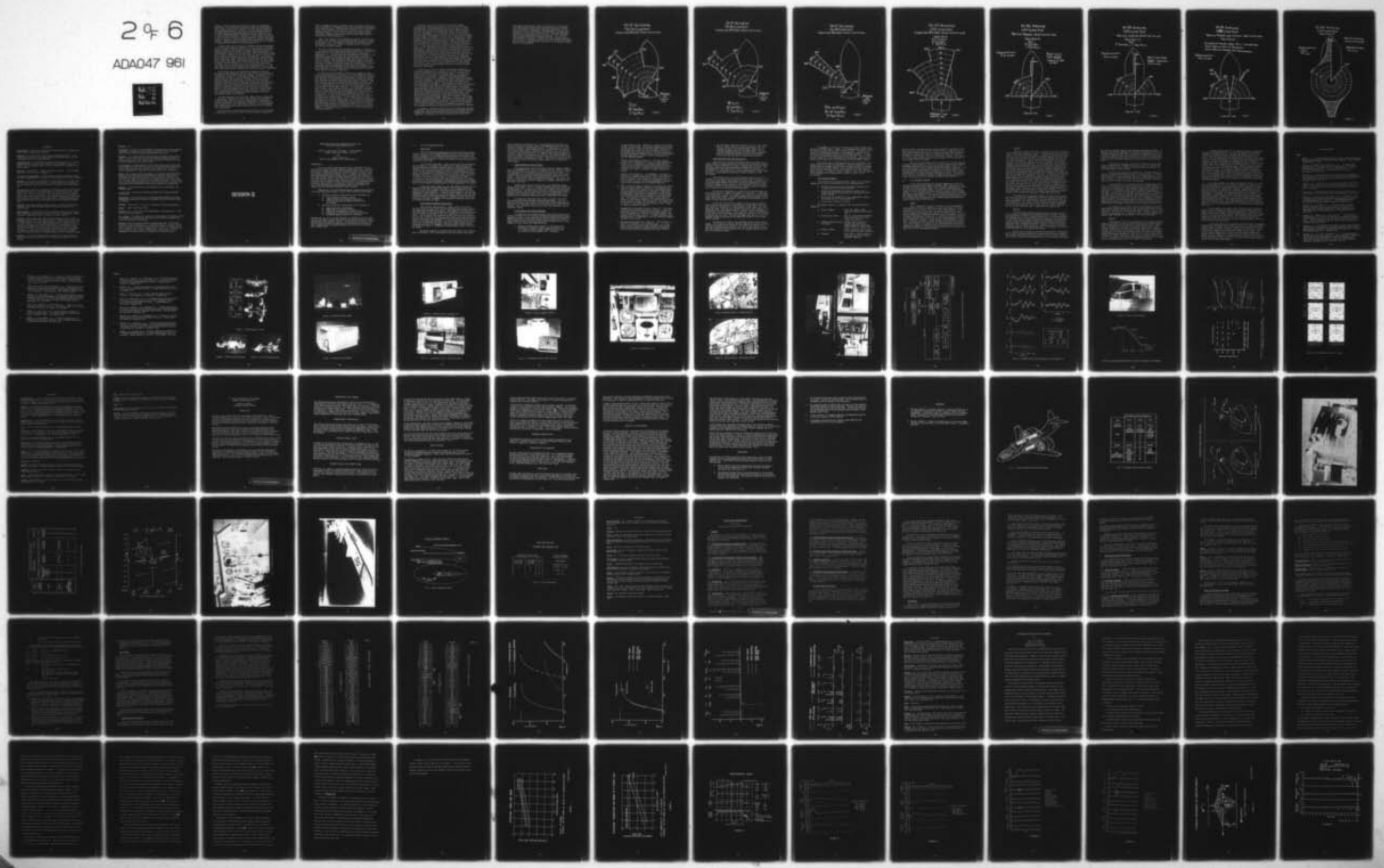
The preceding figures are indicative of helicopter capabilities aboard ships of the smallest size intended for VSTOL operations. As would be expected operational capabilities are improved for the larger aviation designed ships. Figure 4 shows the allowable wind envelope for the SH-3H and LPH class ships. The reduced operating limits for winds in the 015-090 degree segment is due to turbulence downwind of the flight deck island. Notice that for the aviation class ships the allowable wind limits are identical for day or night operations; obviously due to larger flight deck, greater obstruction clearances and better night lighting aids.

The foregoing discussion of helicopter capabilities was presented for both background and comparative purposes. Clearly this is the kind of capability the Navy hopes to duplicate or even improve for shipboard VSTOL operations. Keep in mind that the two helicopters cited in Figures 1 through 4 have demonstrated an

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PROCEEDINGS OF NAVY/NASA VSTOL FLYING QUALITIES WORKSHOP, HELD --ETC(U)
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ability to hover in direct crosswinds of 35 knots for land based operations. Yet aboard ship the crosswind limits are significantly less; primarily due to pilot inability to effect prevision hover in the turbulent environment. For many of the ship classes considered for VSTOL operations, ship superstructure and other obstacles will preclude airplane approaches and landings from all azimuths in order to achieve desired headwinds. Likewise it becomes unduly restrictive on ship operations to require heading changes for aircraft launch and recovery. Expansion of the omni-directional wind envelopes for VSTOL aircraft, beyond the capability exhibited for helicopters, is desirable to achieve greater VSTOL-ship operating flexibility.

To better appreciate the degree of handling qualities improvements required for Navy shipboard operations, at least as these operations are now intended, a look at present Harrier capabilities is revealing. Figures 5 and 6 show the takeoff and landing wind limitations for AV-8A operations aboard the LPH class ship. These AV-8A Harrier limits may be directly compared to the SH-3H limits of Figure 4 since the ship motion limits and operating deck spots are identical. Now stepping down in ship size, Figure 7 shows the allowable wind envelope for the AV-8A and LPD class ship; sized between the LPH and CG-26 class ships with a flight deck roughly 200 ft long by 80 ft wide. The wind limits of Figure 7 are for the most aft of the two LPD landing spots but wind limits for the forward spot are only slightly reduced. For LPD class ships night vertical landings are not permitted. Nor are night VTO or day VL operations recommended when ship deck motion is significant.

The preceding data is not intended to denigrate the Harrier, particularly when remembering that the basic design and technology of the AV-8A is of late 1950's early 60's vintage. As a matter of fact, in defense of the Harrier, the shipboard operating flexibility is greater than the data of Figures 5 through 7 would first indicate. For those ships from which the Harrier operates, deck space and obstacle clearance are large enough that the airplane can always be headed into the relative wind to minimize inherent out-of-wind control problems. Using this flexibility the Harrier routinely conducts VTO or VL operations with winds from any direction as indicated in Figure 8. The small heading sector where operations are precluded is due to turbulence generated by ship super-structure. Clearly this "any heading" aspect is paramount for VTOL operations where ship deck design permits this flexibility.

From this background of existing Navy VSTOL aircraft capabilities I would like to address some of the key paragraphs and requirements of MIL-F-83300. But first a given. The validity of the desired operational capability for Navy VSTOL (DD963 ships in adverse weather and sea conditions) is not argued here. Rather it is the challenge that aerodynamicists and control specialists must accept in developing a VSTOL design.

The first point of consideration in MIL-F-83300 is the stipulation of paragraphs 3.1.2 and 3.1.4 that the flying qualities requirements

apply to asymmetric stores and lateral center of gravity asymmetries. This requirement will undoubtedly have major design impact but deserves early design attention. The high cost of weapons such as the Harpoon missile, will preclude routine jettison just to be able to make a shipboard landing. In fact, the very cost of some weapons dictate that normal training operations are conducted with single weapons, deliberately creating asymmetries.

Some of the luxuries of MIL-F-83300 that the Navy can easily give up appear in the definition of operational flight envelopes of Table I of paragraph 3.1.7. The suggested requirement to perform VTO and VL operations at 10,000 ft or hover at cruising ceiling is excessive for any Navy intended missions.

The 35 kt rearward and sideward flight requirement of paragraph 3.1.7 and Table I is derived from helicopter experience. Similarly the trimmed hover in 35 kt winds from any direction as required by paragraph 3.2.1. Together these two requirements will probably be the determining factor in sizing the VTOL control moment capability. Experience suggests that satisfying these requirements will be difficult; to date no VTOL airplane has been able to hover in more than a 20 kt crosswind. The difference in crosswind capability between helicopter and Harrier operations aboard ship is evidence of the need for greater crosswind capability for new Navy VTOL airplanes. If fulfilled, these two requirements (35 kt rearward and sideward flight plus trimmed hover in 35 kt wind from any direction) will do much to ensure shipboard operating flexibility.

The next area of MIL-F-83300 I would like to comment on is the control characteristics of paragraph 3.2.3. The turbulence associated with shipboard flight operations dictates that some amount of control, over and above trim requirements, be provided to counter gust upsets. Both helicopter and Harrier operations also support the idea that all three aircraft axes are perturbed simultaneously by turbulence. However, the rank ordering of the numerical requirements of paragraph 3.2.3., indicating that yaw is the critical control element, is contradictory to VTOL flight experience. The requirement as stated seems to place undue reliance on single rotor helicopter background data. For VTOL airplanes, experience suggests that the roll axis requires greater control power and response; then the pitch axis with yaw axis last. The actual numerical requirements of Table IV of paragraph 3.2.3.1 have not been verified by any flight test data due to flight safety considerations. In fact, demonstration of this requirement for contract validation may only be feasible using moving base simulators instead of flight tests. For want of more definitive data with regard to these simultaneous attitude changes, the present MIL-F-83300 requirements are considered satisfactory. As a point of emphasis, please note that the requirement for simultaneous attitude changes are superimposed upon the 35 kt trim in a wind from the most ciritical direction.

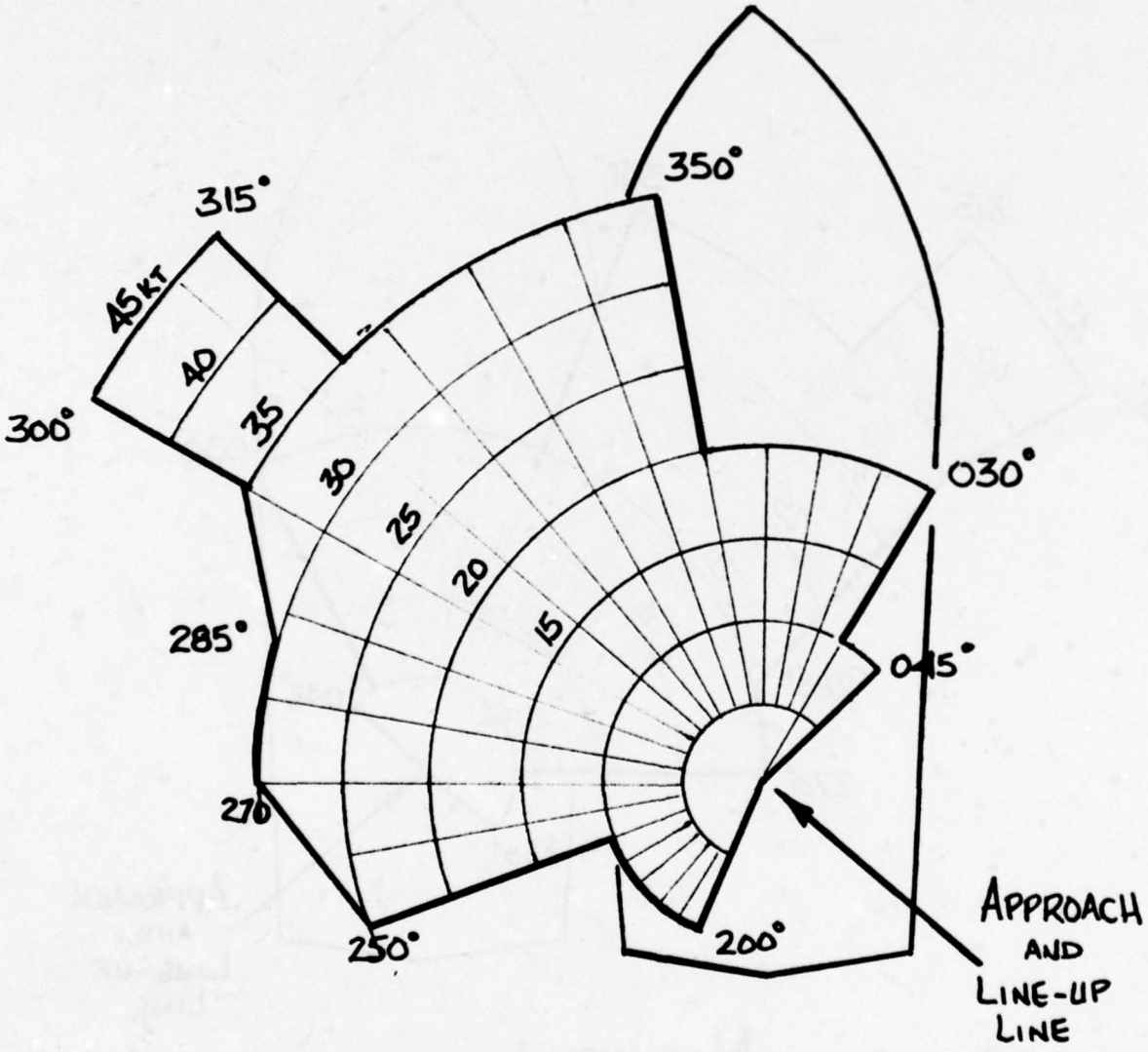
Another key area of MIL-F-83300 is the vertical flight characteristics specified in paragraph 3.2.5 and the following sub-paragraphs. These requirements are the very essence of VTOL aircraft. At first glance the specified Level 1 thrust-to-weight ratio of 1.05 appears to be nothing new. Closer scrutiny shows that this requirement is to be satisfied for the 35 kt trim in any direction while maintaining the control reserve for the simultaneous attitude changes, paragraphs 3.2.1 and 3.2.3.1 respectively. Several designers have criticized the need for all three requirements (T/W, 35 kt trim and 3-axis attitude changes) as unduly restrictive due to payload limitations for vertical takeoff. From my own experience with the AV-8A and CL-84 shipboard operations, I prefer an opposite view. If these requirements are levied at design conception an analytical and experimental data base will be developed to track the requirements. Then flight test results correlated with analytical and experimental predictions will permit precise definition of the real vertical takeoff weight under varying wind and ambient conditions. This analytical and experimental data base are not available for the AV-8A Harrier and to further compound the problem U.S. shipboard flight tests have been conducted without the necessary flight test instrumentation. Thus nearly all Harrier/ship limitations are based upon pilot comments tempered with an added margin for the "average fleet pilot." Some of these limits are known to be conservative; but being unable to define existing limits it is unsafe to predict additional capabilities.

A final point I'd like to address concerns the discussion of atmospheric disturbances in paragraph 3.7 of 83300. This paragraph places responsibility upon the procuring agency to identify the discrete gusts, wind shear or turbulence models to be used by the contractor in his analyses. For Navy applications atmospheric distrubances should also be expanded to include flight deck motions due to sea conditions. Clearly the Navy needs to develop and publish a mathematical model of the turbulent air wake representative of small ships such as the DD963. A scale model wind tunnel test of a smaller FF1052 class ship has been conducted to study this turbulence but a mathematical model has not yet been developed. The FF1052 turbulence model, when available, and others like it are needed to define the maneuvering requirements for countering turbulence and gust upsets and to assess the impact on control systems design. Similar handling qualities problems also exist due to flight deck motion. But at least ship motion models of the DD963 and other ships are available in recently published reports of the David W. Taylor Naval Research and Development Center. The impact of ship motion on VSTOL airplane design now needs to be defined. If the design implications of ship turbulence and motion prove too costly for aircraft development, it may be cheaper to seek relief through ship design efforts to streamline ship decks and superstructure and improve ship stability.

In summary, a challenge has been issued to the handling qualities specialists. The Navy has identified a desired operational capability seeking VSTOL operations from small ships in severe weather and sea conditions. Helicopters are not now satisfying this operational

requirement and the Harrier falls even further short of the mark. The current VSTOL handling qualities specification, MIL-F-83300, does not adequately address Navy shipboard requirements, but the framework is good. Conceptually, the requirement for simultaneous satisfaction of three key criteria (trim in 35 kt wind from worst direction, attitude change about each axis, and $T/W \geq 1.05$) does much to ensure shipboard operating flexibility. It is now the responsibility of the Navy to identify the ship operating environment in terms of turbulence spectra, winds over the deck, ship motion and visibility to support better definition of the numerical requirements of a specification.

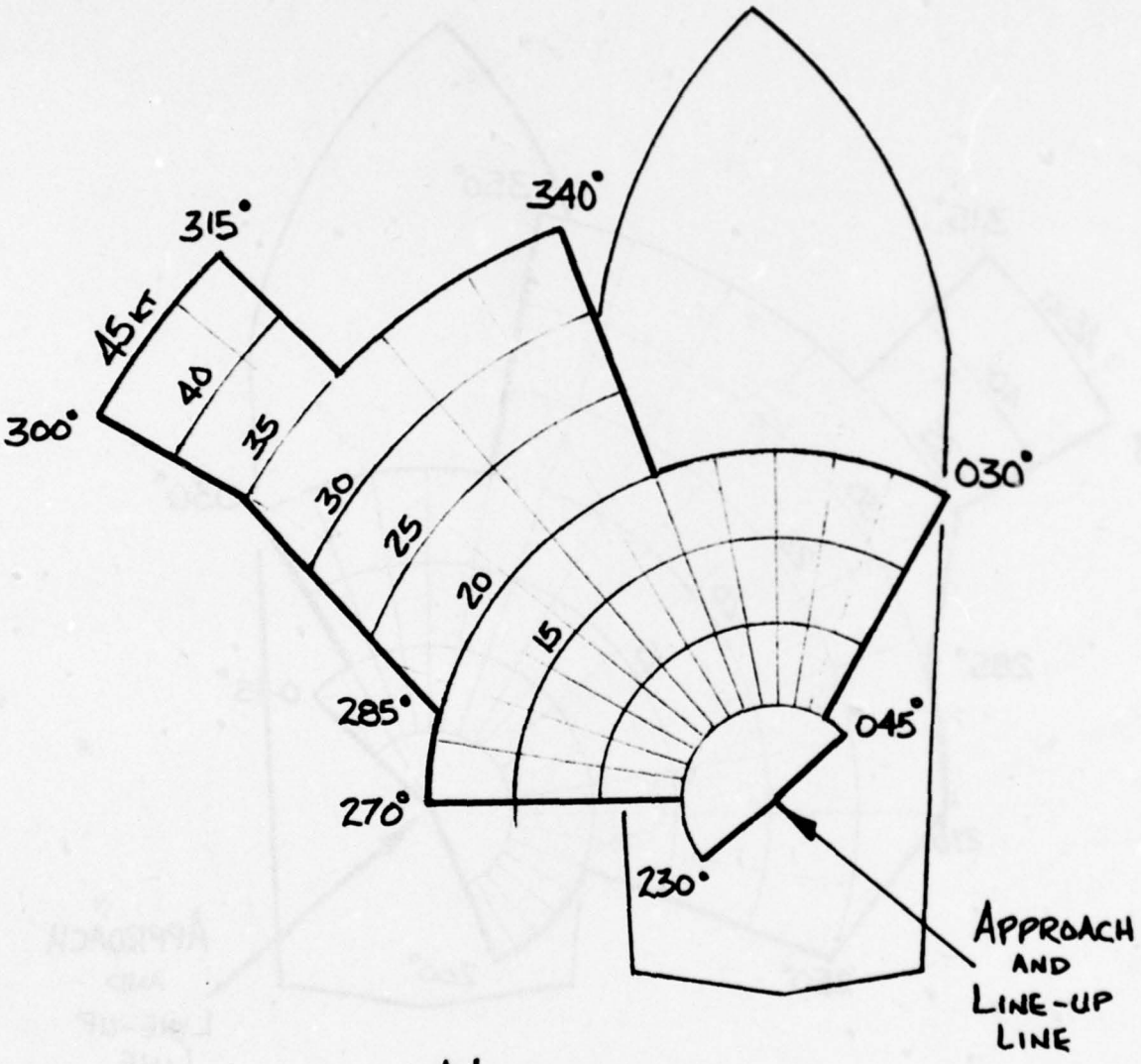
SH-2F Helicopter
CG-26 Class Ship
Launch and Recovery Wind Limitations



DAY
8° SHIP ROLL
1° SHIP PITCH

FIGURE 1

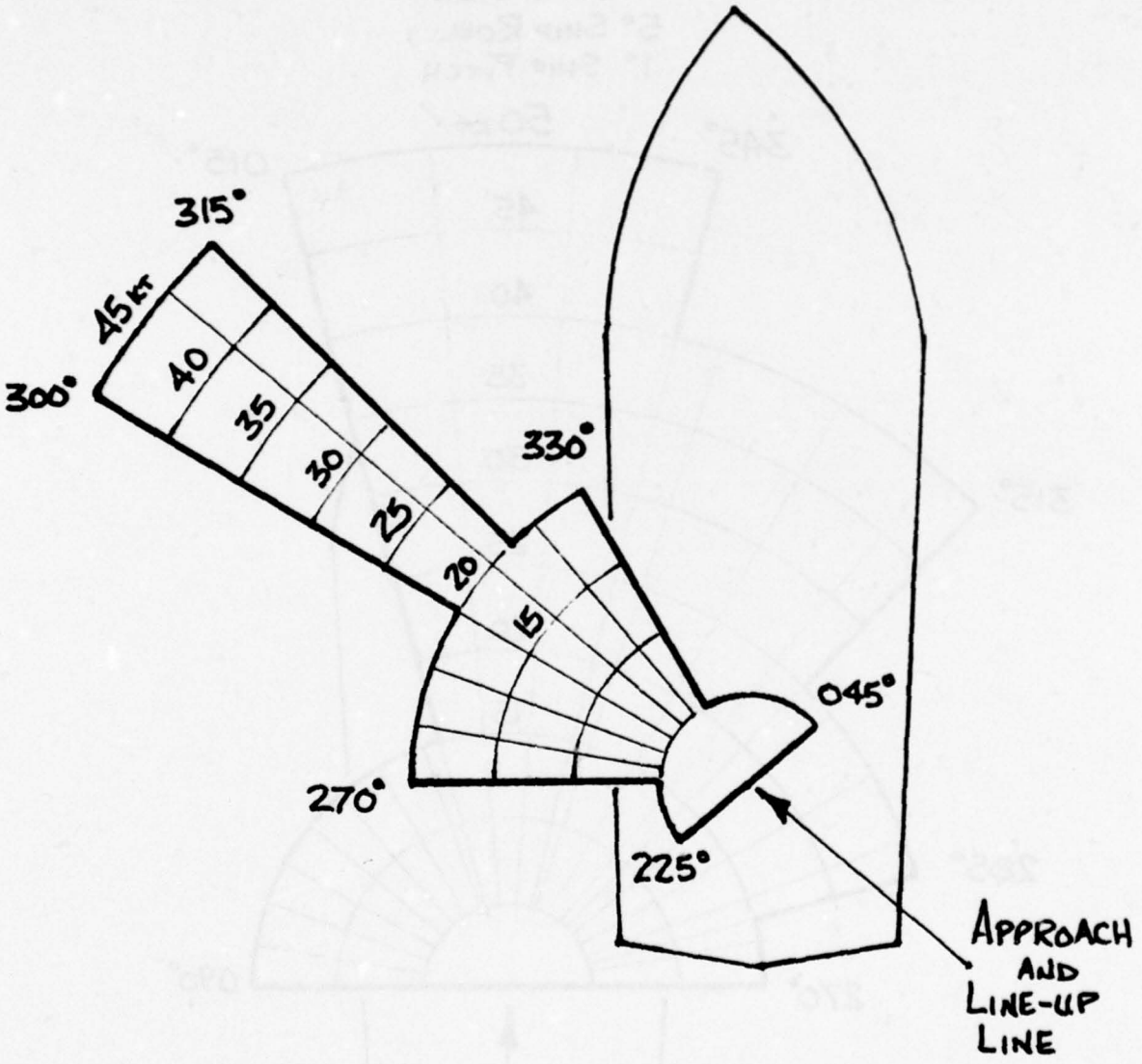
SH-2F HELICOPTER
CG-26 CLASS SHIP
LAUNCH AND RECOVERY WIND LIMITATIONS



NIGHT
8° SHIP ROLL
1° SHIP PITCH

FIGURE 2

SH-2F HELICOPTER
CG-26 CLASS SHIP
LAUNCH AND RECOVERY WIND LIMITATIONS



DAY OR NIGHT
8°-13° SHIP ROLL
5° SHIP PITCH

FIGURE 3

SH-3H Helicopter
LPH Class Ship
Launch and Recovery Wind Limitations

Deck Spot 5
Day or Night
5° Ship Roll
1° Ship Pitch

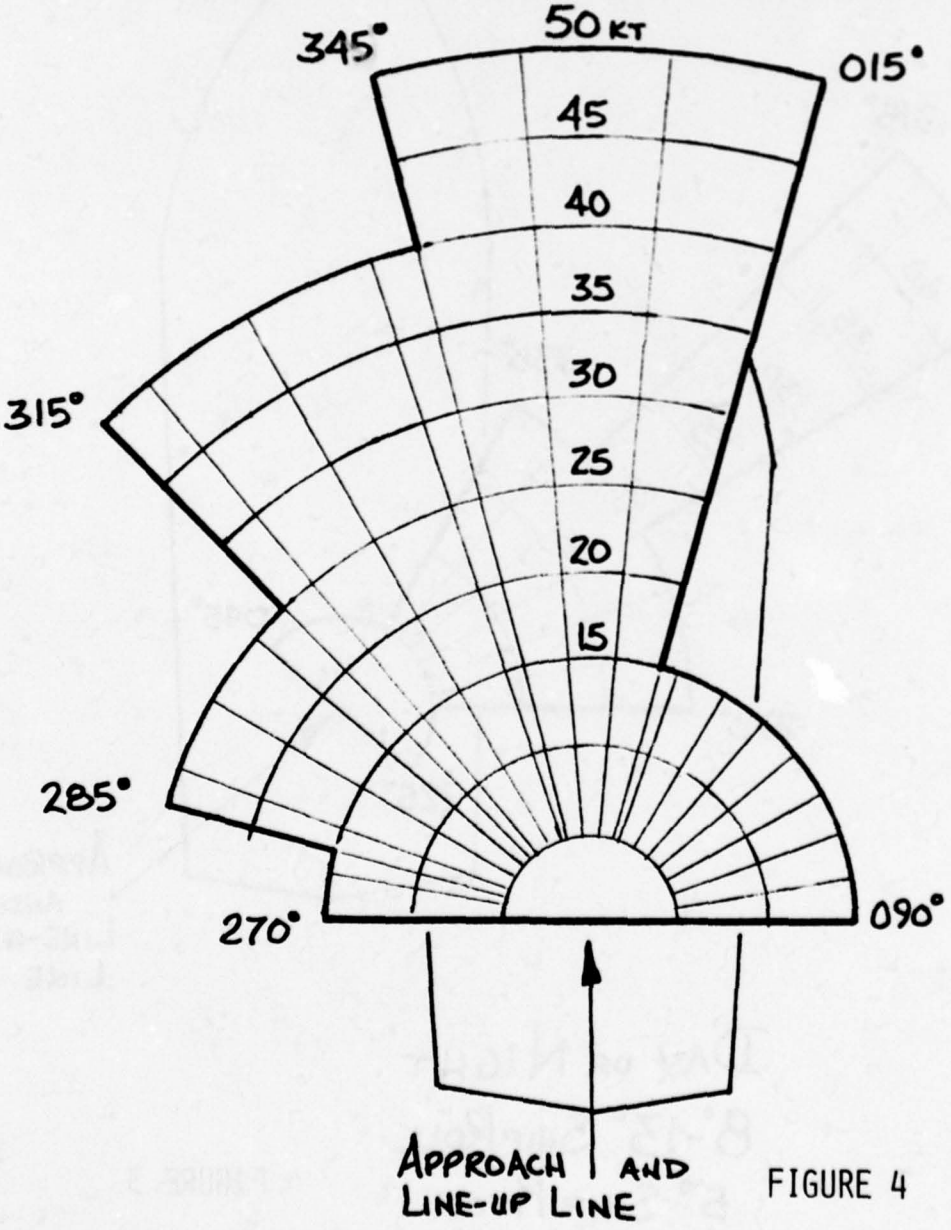


FIGURE 4

AV-8A AIRPLANE
LPH CLASS SHIP
VERTICAL TAKEOFF WIND LIMITATIONS

DECK SPOT 5
DAY
5° SHIP ROLL
1° SHIP PITCH

CROSSWIND LIMIT
10 KT OR LESS

NIGHT LIMITS
SAME EXCEPT
CROSSWIND 5KT
OR LESS

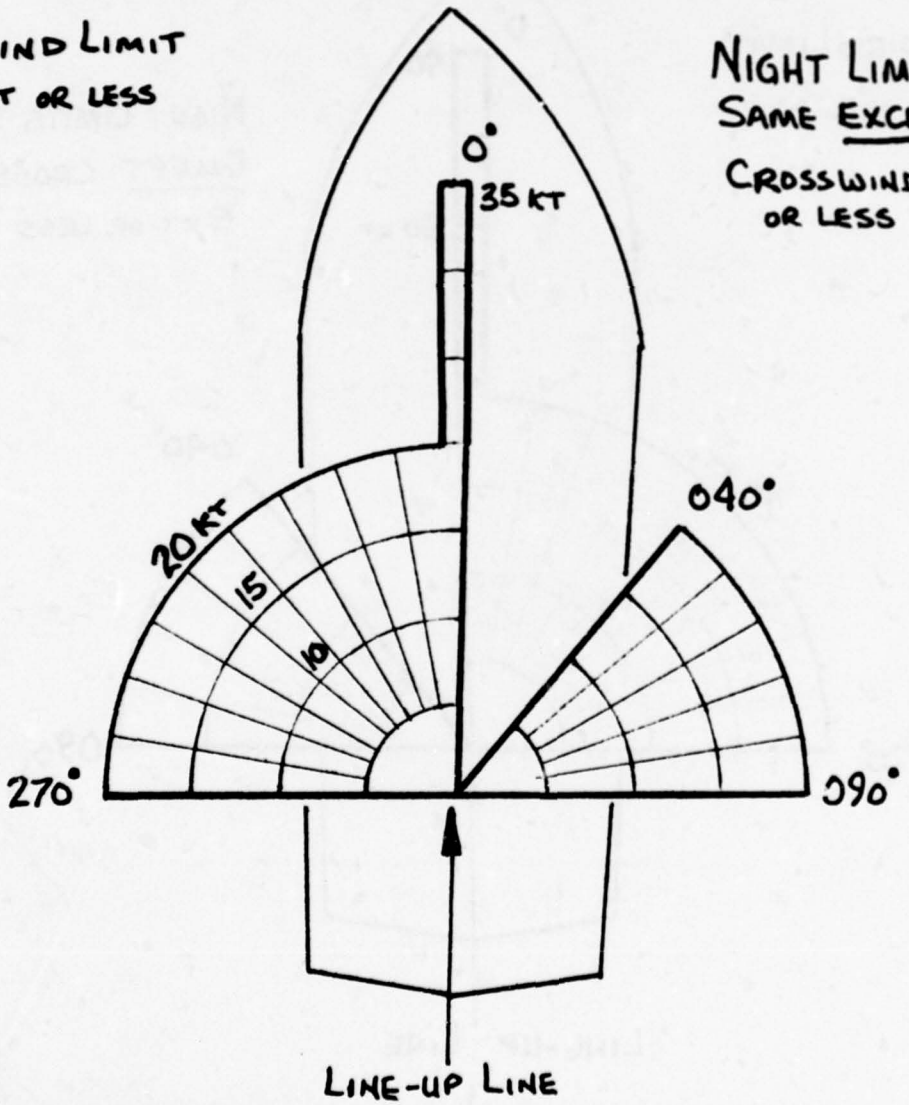


FIGURE 5

AV-8A AIRPLANE
LPH CLASS SHIP
VERTICAL LANDING WIND LIMITATIONS
DECK SPOT 5
DAY
5° SHIP ROLL ; 1° SHIP PITCH

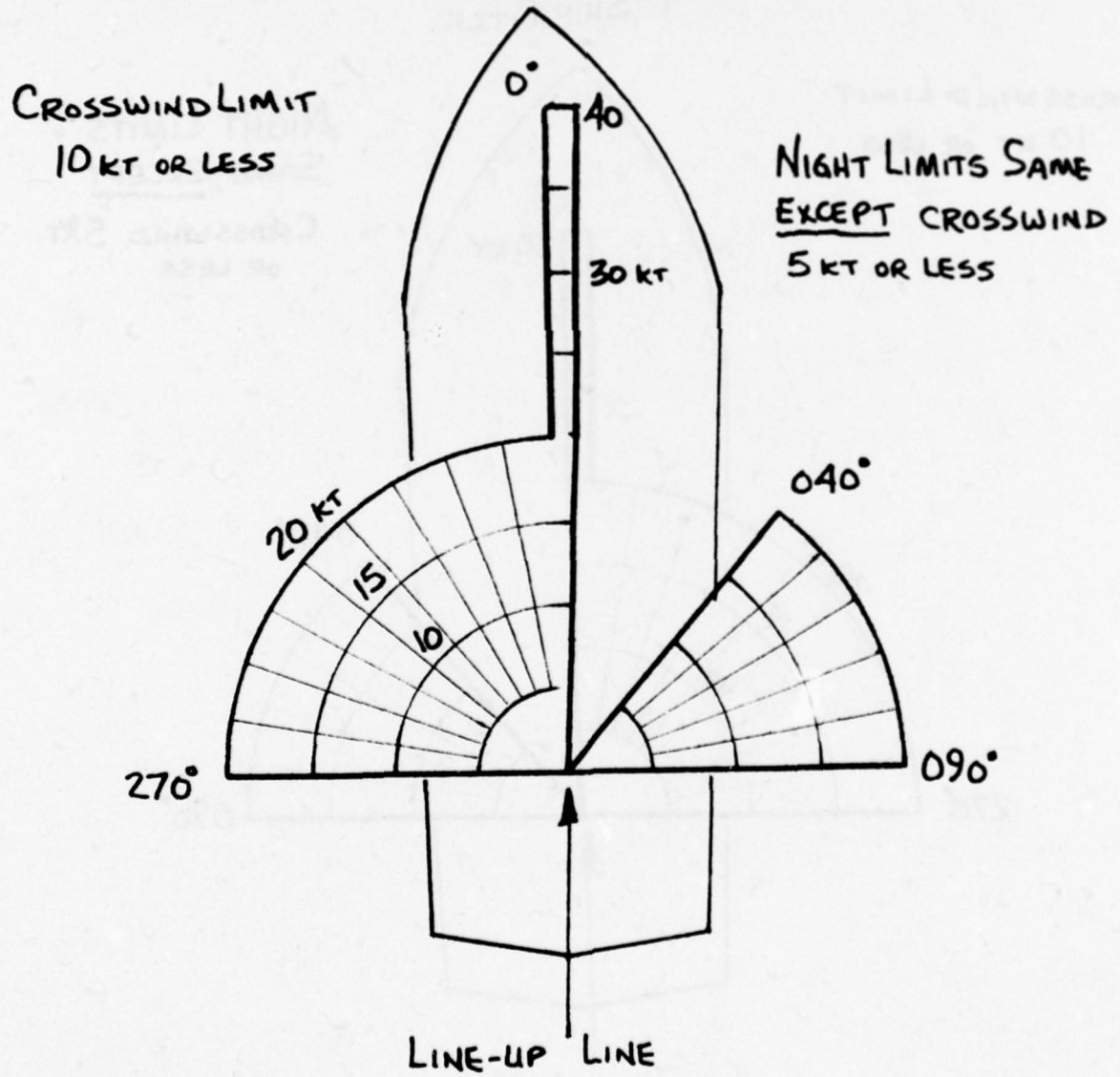


FIGURE 6

AV-8A AIRPLANE
LPD CLASS SHIP

VERTICAL TAKEOFF AND LANDING WIND LIMITATIONS
DECK SPOT 2

NO CROSSWIND ALLOWED ABOVE 20 KT WIND OVER DECK
NIGHT VERTICAL LANDING PROHIBITED
NIGHT VERTICAL TAKEOFFS NOT RECOMMENDED

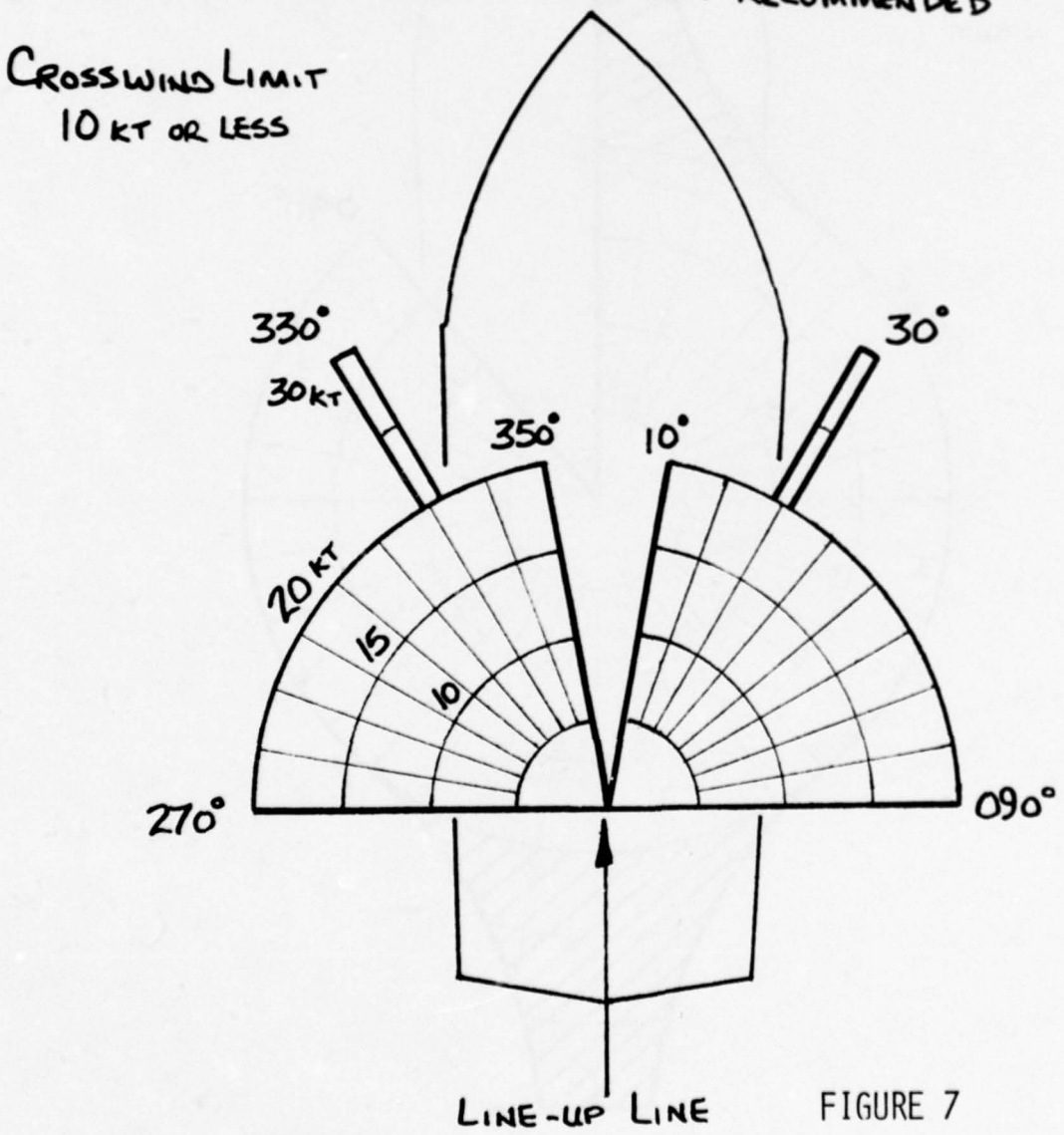


FIGURE 7

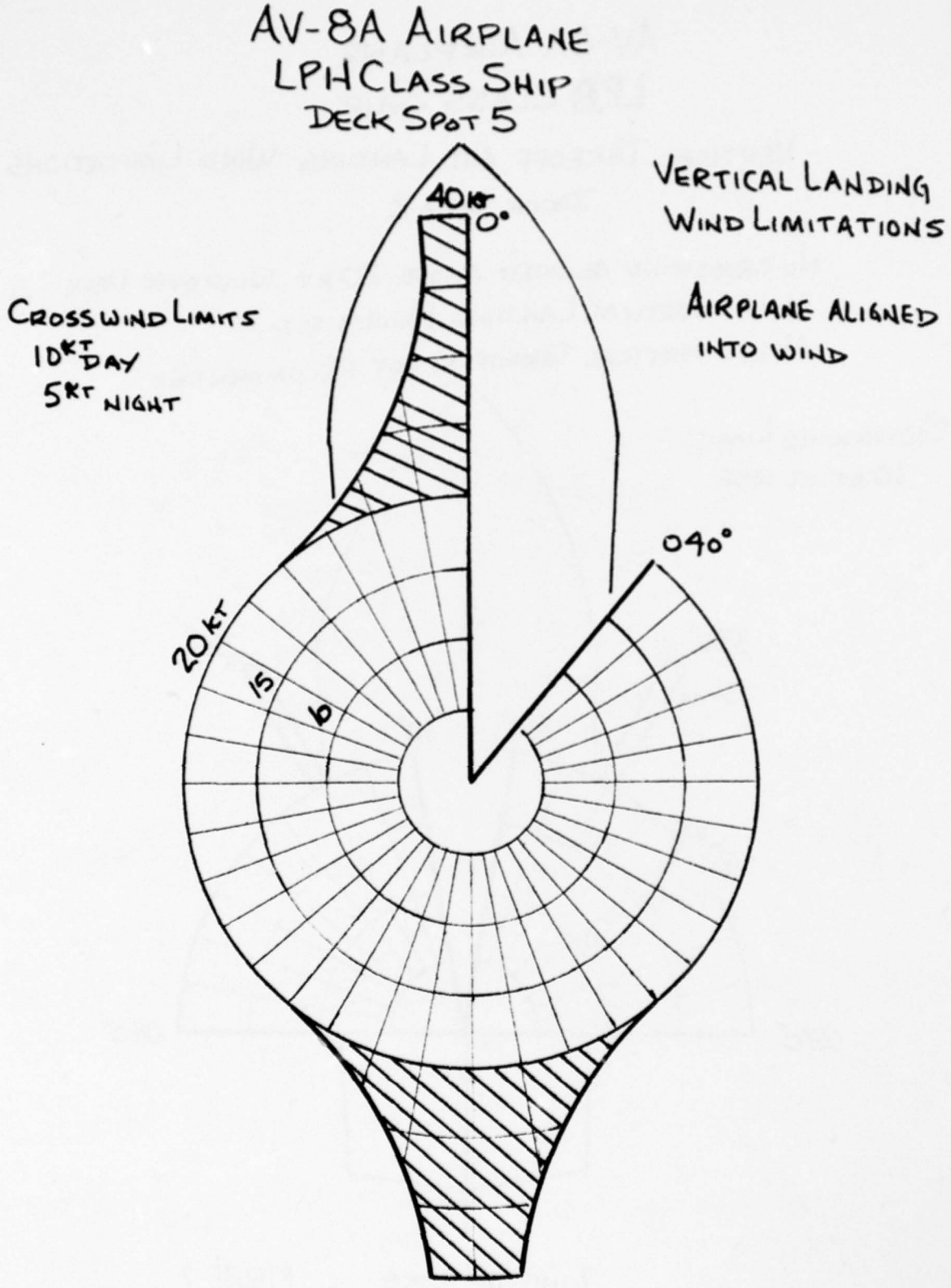

AV-8A AIRPLANE
LPH CLASS SHIP
DECK SPOT 5
VERTICAL LANDING
WIND LIMITATIONS
AIRPLANE ALIGNED
INTO WIND
CROSSWIND LIMITS
10KT DAY
5KT NIGHT
40KT
0°
040°
20KT
15
10

FIGURE 8

DISCUSSION

Andie Byrnes: Do you really think that the Navy will buy an airplane that doesn't have any engine-out capability?

Hutchins: No, I don't think that they would deliberately buy it. But I think that we would end up by making operational restrictions to try and accommodate some form of those failures.

Roman Koneswicz: You mentioned the thrust-to-weight ratio of 1.1 Are you suggesting that the current MIL F-83300 should be changed to read 1.1? I believe that it currently states 1.05 with a special 0.1 g capability for height control.

Hutchins: You are right. I made a mistake in my quote. It (MIL F-83300) does state 1.05 with a 0.1 g capability.

Lt. Col. J. E. Iles, USMC: Is there going to be any more emphasis placed on design requirements and assessment in ground effect than exists at present?

Hutchins: I don't have a good answer for that, Bud, but as it reads right now, the specs apply to IGE and OGE. I don't think that we at present have the analytical capability to predict and estimate what ground effects are.

Lt. Col. Iles: Excuse me, the reason for my question comes from Mr. Lacey's presentation relative to the demonstration of some of the critical flight points. As a result, a lot of our flight data is OGE while our critical task is IGE. What I was getting at was a closer look at the influence of being closer to the ground. From a test technique standpoint, I understood what Mr. Lacey was saying, but I'm hoping that we can get something a bit more definitive down in the region where all the trim changes are taking place.

Hutchins: We're very definitely going to have a control system that performs much better IGE than typically what the Harrier pilot does for himself today.

Peter Nicholas: I would like to raise a question relative to the 35 knot wind criteria from any direction for VTOL aircraft. By comparison, nobody requires a fixed wing aircraft to land in a 35 knot tailwind.

Hutchins: From my experience, the critical direction will not be from a tailwind direction for a VTOL airplane anyway. The helicopter people right now (NATC pilots) have clearly demonstrated that they can land with up to a 10 knot tailwind. Now, the fleet operators will not permit that type of operation to appear in the flight manual because as a helicopter pilot, they are never allowed to train or operate under those kinds of tailwind conditions. So they are very definitely concerned that such information not appear in a fleet manual and thereby make it possible for a ship's skipper to tell the pilot to do something which he is not comfortable doing.

Nicholas: I was really thinking of the situation of aligning the ship, while at sea, with the relative wind for landings and thereby reduce the problem.

Hutchins: Yes.

Eric Baitis: Relative to your comments on the importance of ship-generated turbulence, are those based upon Harrier experience or are those based upon the small LAMPS helicopter experience that we've had?

Hutchins: It is based primarily upon helicopter experience aboard small ships. But then there also is the CL-84 experience aboard the Guam. In addition, when it got real turbulent with the Harriers during our initial operating experience, they didn't operate.

Lt. Col. Iles: I would personally qualify your remarks as to ship motion to the night time situation when you are relying upon external ship structure or other reference for providing cues to ship motion. There is a strong dependence upon being able to see the horizon for a reference.

Baitis: May I make an amplifying comment? The initial experiences which established the importance of ship-generated turbulence were at NATC on the Bowen tests with relatively small aircraft, the H-2 I believe. We then went and conducted a similar set of experiments for the Coast Guard with a smaller (3000 ton) ship and a much larger helicopter. In the latter case, the turbulence problem was gone. That aircraft didn't respond to the turbulence in the same manner as the smaller aircraft on a bigger ship.

Hutchins: Possibly there are some peculiarities in the individual ship superstructures.

Lt. Col. Iles: We had some turbulence problems when flying the Harrier on the Guam.

Andie Byrnes: Do you foresee any future requirements coming up for STOL landings and conventional landings in emergency situations for these types of machines?

Hutchins: Aboard ship, I cannot see a conventional landing requirement.

Byrnes: I didn't mean aboard ship.

Hutchins: Yes, I can foresee some requirements to STOL operation. I don't know yet what they might be.

G. P. Cragin: If the Navy were going to be entertaining multi-engine aircraft for engine-out considerations, then what would the thrust-to-weight ratio be for the engine-out requirement?

Hutchins: That is beyond my ability to answer right now. I don't know what we will end up specifying. We would prefer that the aircraft have an ability to return to the deck, but we might not be able to require a 1.05 thrust-to-weight ratio when one engine is out. Maybe 1.0 or something like that, especially since we have a landing gear on the aircraft that is designed for a vertical velocity at landing of 15 feet per second.

SESSION II

CAPABILITIES OF THE NAVY VARIABLE STABILITY X-22A FOR V/STOL FLYING QUALITIES R & D

by

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INTRODUCTION

The X-22A V/STOL Flight Research Facility represents the only Navy owned in-flight simulation capability applicable to hover, low-speed and transition flight investigation of fixed wing V/STOL flying qualities. The facility, consisting of the X-22A variable stability aircraft, fixed based ground simulator and telemetry van, is currently being operated by the Flight Research Branch of Calspan Corporation under the cognizance of the Flight Dynamics Branch of the Naval Air Development Center. The combination of a wide range of flight conditions, vehicle and control dynamics, a portable MLS for guidance and the recent addition of a programmable Head-Up Display (HUD) provides a significant research and development capability for investigating flying qualities, stability and control and flight safety of existing and proposed V/STOL aircraft.

Specifically, the X-22A research facility capabilities are suited to the following general aspects of Navy V/STOL research and development:

- Simulation of generic characteristics for the purpose of:
  - a) verifying ground simulator results;
  - b) flight testing control/display interfaces;
  - c) validating existing and proposed specification requirements;
- Simulation of specific configurations for the purpose of:
  - a) supporting aircraft development;
  - b) addressing ad hoc dynamic problems;
  - c) flight crew training prior to first flight;
  - d) developing and validating pilot/system interfaces;
  - e) developing improved flight test techniques.

Although this list is by no means complete, it nonetheless serves to point out the wide range of present and future V/STOL problem areas which may be addressed with this research facility. The purpose of this paper is therefore to describe briefly the capability of each element of the facility, and to summarize past and present programs using it that have addressed some of these areas.

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1.0 THE X-22A RESEARCH FACILITY

Basic X-22A

The X-22A aircraft was developed by the Bell Aerosystems Company during a seven-year effort managed by the Naval Air Systems Command (NASC) and was designed to be a variable stability aircraft from the start with Calspan responsible for the variable stability system. In 1970, the Naval Air Systems Command awarded a contract to Calspan to begin flying qualities research with the X-22A.

As is evident from Figure 1, the X-22A has four ducted propellers and four engines. The engines are connected to a common system of rotating shafts which distribute propulsive power to the four propellers. Changes in the direction of the thrust vector are accomplished by rotating the ducts, which are interconnected so that all rotate through the same angle. Thrust magnitude is determined by the collective pitch of the four propellers and this is controlled by either one of two levers, selectable in flight. One lever is very similar to a conventional helicopter "collective stick" and the other lever can be moved fore and aft similar to a throttle. Normal-looking pitch, roll and yaw controls in the cockpit provide the desired control moments by differentially positioning the appropriate control elements (propeller pitch or elevon deflection) in each duct.

In hovering flight (Figure 2), the X-22A employs fore and aft differential blade pitch for pitching moments, left and right differential blade pitch for rolling moments, and left and right differential elevon deflection for yawing moments. In forward flight (Figure 3), fore and aft differential elevon deflection is used for pitching moments, left and right differential elevon deflection for rolling moments, and left and right differential blade pitch for yawing moments. A mechanical mixer directs and proportions the pilot's commands to the appropriate propellers and elevons as a function of the duct angle.

X-22A Variable Stability System (VSS)

There are four VSS controllers - thrust, pitch, roll and yaw - and three artificial feel servos for the evaluation pilot cockpit controls, each employing electrohydraulic servos. When rigged for VSS flight the left-hand flight controls are mechanically disconnected from the right-hand flight controls and connected to the set of VSS pitch, roll and yaw feel servos. The VSS thrust servo operates the boost servo for the collective pitch system. VSS pitch, roll and yaw servos operate the right-hand flight controls, moving the same linkages which are moved manually by the right-hand pilot in normal non-VSS flight. (In fact, these same actuators serve a dual role by providing artificial feel for the primary flight control system when the VSS is not engaged.) Phasing of these control motions to the blades and elevons is accomplished by the mechanical mixer as for normal flight.

During VSS operation, the evaluation pilot occupies the left-hand seat in the cockpit. The system operator, who also serves as the safety

pilot, occupies the right-hand seat. The evaluation pilot's inputs, in the form of electrical signals, operate the appropriate right-hand flight controls through the electrohydraulic servos. In addition to the evaluation pilot's inputs, signals proportional to aircraft motion and relative wind variables (for example, angle of attack and pitch rate) are fed back to move the right-hand controls in the required manner and thus modify the aircraft's response characteristics as desired. The response-feedback and input gain controls are located beside the safety pilot and are used to set up the simulation configurations in flight. Note that the evaluation pilot cannot feel the basic X-22A control motions caused by the variable stability system.

Unique Features of the X-22A VSS

One unique feature of the X-22A VSS is that the response feedback gains are programmable with velocity throughout the full range of airspeeds, from -30 knots rearward through zero to 150 knots forward airspeed. This is accomplished by a multi-channel function generator which receives its airspeed input from the LORAS (Linear Omnidirectional Resolving Airspeed System). LORAS was developed by Calspan specifically for the X-22A. Recently, a second LORAS - much smaller than the original - was added to the nose boom to measure the vertical component of airspeed, specifically for VSS work in the hover.

Another unique feature of the X-22A is the Feedforward Flight Control System (FFCS). This is a limited authority, precision control system which acts like a vernier on the basic X-22A flight control system during VSS operation. The FFCS makes it possible to achieve extremely high precision in positioning the actuators for the X-22A aerodynamic controls - propeller pitch and elevon angle. Such control system precision is required for the satisfactory operation of the "closed-loop" VSS airplane.

A special Test Input Unit (TIU), which is a part of the X-22A VSS, greatly facilitates in-flight calibration procedures. This unit generates electrical step, doublet, or pulse inputs (whose magnitude and time scale are selectable) which can be inserted into any of the four VSS channels. Thus calibration records can be taken with repeatable, easily controlled, inputs.

X-22A Guidance and Display Equipment

In addition to the variable stability and control capability afforded by the VSS, the X-22A aircraft systems include guidance and display equipment to permit variable guidance and variable display investigations. These systems consist of several computational units plus both a Head-Up Display (HUD) unit and a Head-Down Display (HDD) cathode ray tube; basic elements of these systems are summarized below.

1. Microwave Landing System (Figure 4). This system was developed as a portable tactical landing system by the U. S. Army Electronics Command (ECOM) and built by the AIL Division of Cutler-Hammer, Inc. It operates

at approximately 15 GHz, employs the scanning beam technique and has co-located DME. The airborne equipment in the X-22A decodes absolute azimuth and elevation angle information from the landing site as well as error information from the approach path and selected glide-slope. The absolute position data from the MLS are blended with on-board accelerometer data through complementary filters to obtain smoothed position data for guidance purposes.

2. Airborne Analog Computer (Figure 5). This unit performs guidance data transformations, guidance command computations, flight director computations, and permits additional stability/control variations including limited model-following (command prefiltering). Fourteen (14) potentiometers are located in the cockpit to provide in-flight variations if desired.

3. Interface Unit (Figure 6). This equipment is analogous in function to a communications central office: the various raw data and processed data channels can be patched from one system to another. These systems include the VSS, MLS, airborne computers (digital and analog) programmable displays (head-up and head-down) and the telemetry down-link.

4. Smiths Industries Graphics Generator and Airborne Data General NOVA 3/12 Digital Computer (Figure 7). This equipment provides the capability to generate display information formats for presentation either head-up or head-down. Complete programming flexibility permits an essentially unlimited range of calligraphic symbology and alphanumerics for the replication of any existing electronic format or the design of new ones. The computer is controlled from a remote miniature terminal in the cockpit (Figure 8), so that any desired format can be selected in flight for presentation. The terminal can be placed in a horizontal position when not in use in order to reduce the visual obstruction.

5. Programmable Analog Symbol Generator (Figure 9). For simpler display formats presented head-down, this unit is capable of producing as many as 32 different calligraphic symbols, and was the equipment used in the Task III control-display investigation to be discussed shortly. In-flight selection of the desired format is accomplished by ten (10) individual blanking switches in the cockpit.

6. Head-Down Display (HDD) Unit (Figure 10). This equipment is a Kaiser 5" CRT mounted in the instrument panel. It is currently driven by the analog symbol generator, but the capability may be expanded to include use of the programmable digital display generation equipment previously described.

7. Head-Up Display (HUD) Unit (Figures 11 and 12). This equipment is a Smiths Industries Pilot Display Unit (PDU), including CRT, optics and combining glass, mounted on a retractable mechanism above the instrument panel. The retraction arrangement provides the correct eye-to-glass distance for normal HUD viewing and quickly clears the PDU from the ejection envelope for flight safety purposes.

Data Acquisition and Processing System

Since the X-22A aircraft and variable stability systems are extremely complex, requiring monitoring during flight of many more variables than can be easily scanned by the pilot, a sophisticated system for data telemetry, acquisition, and processing was designed for the X-22A. All data pertinent to the flight of the X-22A aircraft (137 channels) are telemetered to a ground station via a pulse-code-modulated "L-band" telemetry link. A more complete description is given in Paper 3 in the Bibliography.

Patch panels in the X-22A aircraft permit selection of the 137 variables to be telemetered from approximately 200 that are available. For the research experiments, approximately 80 flight safety variables (such as bearing hanger vibration levels and various oil temperatures and pressures) are telemetered and monitored; the remaining 57 variables (such as angle of attack, stick control positions, and VSS electrical commands) are of interest to the flying qualities experiment.

The data are telemetered to a ground station and experiment control center housed in a mobile van (Figures 13, 14 and 15). A simplified block diagram shown in Figure 16 summarizes the functions of the equipment in the van during a flight. The primary purposes of the equipment include flight safety monitoring, experiment control and data processing, each of which is briefly described below.

As has been discussed, the complexity of the X-22A aircraft requires constant monitoring of a large number of flight safety variables. This function is performed by the mini-computer in the mobile van. High and/or low limit values for the variables are stored in the computer; the telemetered data is processed through the computer on-line and compared continuously with these limits. In the event of a variable exceeding these preset limits, the teletypewriter unit immediately prints out the variable in question and its value. The high speed paper tape unit acts as an independent backup by printing out on command the values of all the telemetered variables.

The mobile van is used as the experiment control center during a flight. Pilot input and aircraft response variables are monitored on-line with four six-channel chart recorders. The flight test director is in continuous communication with the aircraft and, on the advice of the engineers monitoring the flight variables, can (for example) request the repeat of a calibration record.

The equipment in the van also serves to process the flight data digitally "off-line" after a flight. All telemetered data during a flight are recorded continuously on the bit-stream recorder. For digital data analysis, the appropriate portions of the appropriate channels are selected from the bit-stream recorder, and the format changed to be compatible with the IBM 360/65 computer used for the analyses. This is accomplished through use of the van computer and equipment to produce the required digital tape which is then processed by the IBM 360/65 computer.

Many digital data processing techniques are available for use on flight data from the research experiments. Paramount among these is an advanced digital parameter identification technique developed by Calspan for the Naval Air Systems Command. This technique has been successfully applied to over 300 flight data records during the first two X-22A research programs; an example is given in Figure 17, and a full description of the technique and its applications is given in Paper 4 of the Bibliography.

X-22A Ground Simulator

The fixed-base X-22A ground simulator (Figure 18) is designed to supplement the X-22A aircraft operation in the following manner:

- Perform preliminary tests of experimental programs prior to flight tests in the actual aircraft.
- Develop new experimental hardware and systems, such as control systems and displays prior to installation in the actual aircraft.
- Ground test new equipment and check experimental setups in the aircraft prior to actual flight test.
- Provide pilot training as required.

The ground simulator is composed of the following functional components:

- Digital computer - solves the computer model equations (housed in X-22A mobile van)
- Variable feel system - provides force-position characteristics for pilot's stick and rudder pedal controls
- Variable stability system-electronics - combines inputs from pilot's controls with feedback of computed responses to provide control inputs to computer model
- Cockpit displays - flight instruments used by pilot to fly under instrument conditions
- Interface - patch boards, signal conversion, filtering, and scaling between simulator components

The feel system, variable stability system electronics, and flight instruments duplicate those found in the X-22A aircraft. In addition, the airborne analog computer and either the analog or digital display generation equipment is used with the simulator to duplicate exactly the guidance and display characteristics that are investigated in flight. This replication of the flight hardware ensures precise control over the variables to be investigated prior to flight.

The X-22A ground simulator can also be used as a general aircraft instrument flight simulator. The use of a digital computer, with complete programming flexibility and program tape-storing capacity, greatly enhances the capability of the ground simulator for general simulation. Complex and nonlinear aerodynamic characteristics for either V/STOL or conventional aircraft can be readily incorporated, as can nonlinear control characteristics, or simple linearized equations of motion. Auxiliary systems, such as an ILS approach system or a sophisticated digital adaptive flight control system, can be readily included in the simulation.

2.0 X-22A RESEARCH PROGRAMS

X-22A research programs were initially supported by the X-22A Interagency Steering Group, composed of NAVAIR, AFFDL, NASA-Langley, and the FAA. Starting with the current Task IV program, sponsorship is solely by the Naval Air Development Center. The first two X-22A experiments (Tasks I and II) involved STOL flying qualities research for the landing approach. A third program (Task III), concerning control system, display, and guidance requirements for VTOL aircraft instrument approach and landing, has recently been completed. The Task IV program, currently underway, has as its general goal the expansion of the adverse weather operating capabilities of the Navy's VTOL aircraft.

Task I

Task I (described in Report 1 and Paper 2 of the Bibliography) investigated the effects of longitudinal short-term dynamics on flying qualities for both instrument and visual STOL landing approach. Fifty evaluations were made by two pilots of eighteen combinations of short period frequency and damping at two approach velocities (65 kt, 80 kt) for several representative steep STOL approach paths (6-10 degrees) in both noticeable and negligible turbulence. It is worth noting that essentially no flying qualities data of this type for STOL landing approach existed prior to the Task I program; a major purpose of the program was, therefore, to supply these data in support of flying qualities specifications (e.g., MIL-F-83300). The results of the flight experiment demonstrated clearly that steep STOL approaches under instrument conditions could be performed satisfactorily, given good short-term dynamics as defined by the data, with only ILS information displayed.

Task II

The Task II program (described in Reports 5 and 6) was considerably more ambitious and complex than Task I. Two experiments were run concurrently. The primary experiment (Report 5) again was concerned with flying qualities for visual and instrument STOL landing approach, but this time the investigation centered on lateral-directional dynamics and roll control power requirements. Dynamic variables investigated in the experiment were roll mode time constant, Dutch roll frequency, roll caused by sideslip and yaw caused by aileron. To investigate roll control power requirements, the control power available was electrically limited in the variable stability system for selected sets of dynamic characteristics. Three pilots flew 109 evaluations of 17 sets of dynamic characteristics with several values of limited roll authority for four of these sets; both visual and instrument STOL approaches were performed at a glide slope angle of 7.5 degrees and velocity of 65 knots. A large number of results were obtained from this experiment. Among the most salient were that approximately twice as much roll damping is necessary for satisfactory flying qualities as is required by the flying qualities specification (e.g., again MIL-F-83300), that a definite linearly degrading pilot opinion results from reducing roll control authority past a prescribed minimum amount, and that the roll control power necessary to obtain satisfactory flying qualities is approximately half that prescribed by the flying qualities specifications. All of these results represent hitherto unavailable data to aid the design of future STOL aircraft; the roll control power data in particular has an extremely important impact on such designs, and these data are therefore a significant contribution.

The second Task II experiment (Report 6) explored and expanded the hover and transition capabilities of the X-22A variable stability system; this expansion was a prerequisite for the conduct of the Task III flight experiment. The results of this experiment revealed no fundamental limitations of the variable stability system that might compromise future transition research, and, in fact, the first vertical landings on the VSS ever performed were made to demonstrate the capabilities.

Task III

The third flight research program using the variable stability X-22A aircraft was undertaken to investigate control, display, and guidance requirements for VTOL instrument transitions. The primary purpose of the experiment was to provide meaningful data related to the interaction of the aircraft control system and displayed information characteristics on pilot rating and performance during a steep decelerating descending transition from a representative forward velocity (100 kt) to the hover completely under instrument conditions. Extensive theoretical analyses and ground simulator verifications were used in the design of the 45-hour flight experiment to ensure maximum efficiency.

Thirty-seven in-flight evaluations were performed of combinations of five generic display presentations, ranging from position-information-only to four-axis control directors, and five levels of control augmentation systems, ranging from rate-augmentation-only to decoupled longitudinal

and vertical velocity responses and automatic configuration changes. In addition, new guidance developments of fundamental importance to VTOL instrument terminal area operations, including an Independent Thrust Vector Inclination Command (ITVIC) and a procedure for automatically switching between airspeed and ground speed tracking to account for headwinds and crosswinds, were conceived, designed, and demonstrated during the experiment.

An AN/SPN-42T1 tracking radar system (including a ground radar, a digital computer and a telemetry up-link) was used to locate the aircraft's position in space, generate the required position signals, and send these signals to the aircraft.

The task flown (Figure 19) consisted of a localizer capture followed by a constant-speed acquisition of a 7.5° glide slope. At a point on the glide slope, the deceleration (hence duct rotation) phase of the approach began; a constant deceleration level of approximately .05 g was used. The final portion of the task consisted of the flare, continued deceleration to a hover at 100 feet, and touchdown.

Primary results of the program included the demonstration of an inverse relationship between control complexity and display sophistication, as was hypothesized in the experiment design, and the definition of acceptable and satisfactory control-display combinations (Figure 20). In particular, it was found that the explicit display of translational velocities is required for a satisfactory system, regardless of control system complexity or automation, and that rate-augmentation-only may be acceptable (though still unsatisfactory) only if full control director commands are provided in addition to velocity status information. Analysis of the results in terms of simple pilot-in-the-loop considerations and measured performance and workload were also conducted to provide initial guidelines for the design of future VTOL control-display characteristics.

The interaction of aircraft control system complexity, guidance requirements, display sophistication, and aircraft flying qualities presents a multidimensional research problem whose solution is not yet well understood. The Task III X-22A experiment made a valuable initial contribution to understanding this problem for V/STOL instrument landings, and provided the background for the design of the Task IV experiment.

Task IV

The purpose of the Task IV experiment is to specialize particular aspects of the Task III control-display investigation to configurations that are representative of a particular operational aircraft's capabilities. Specifically, limitations in available control power or SAS actuator authority of some VTOL configurations imply that the augmented aircraft characteristics investigated in Task III may not be achievable. In addition, it is clear that the requirements for satisfactory control-display combinations determined in Task III may be overly restrictive if a breakout to visual conditions is permitted at some point prior to the hover; if a breakout is included, the advantages of using head-up display for the information presentation also require investigation.

To address these questions in a realistic context, the stability and control characteristics of a jet-lift VTOL fighter (the McDonnell-Douglas AV-8B Advanced Harrier) are being simulated with the X-22A as accurately as possible through a terminal area transition (105 kt to hover). With the cooperation of McDonnell-Douglas, a linear model of the AV-8B for two approach profiles was developed, and then methods developed in Report 8 of the Bibliography were employed to define appropriate variable-stability system feedback and feedforward gains. Figure 21 shows example time history responses for the AV-8B model and the X-22A simulation of it for a 65 kt trim approach speed; similar simulation validity was achieved over the entire velocity range both longitudinally and lateral-directionally. In addition, although the thrust inclination of the AV-8B is changed almost instantaneously to effect the deceleration, while the ducts of the X-22A rotate at a constant 5 deg/sec, the difference in drag damping between the two aircraft has permitted accurate simulation of the deceleration characteristics by programming the duct angle changes and using the X-22A control surfaces in a collective rather than differential fashion.

The flight program will address two approach profiles: one using an initial velocity of 65 kt with thrust rotation to the vertical simulated at approximately 0.5 nmi from hover, and the other with an initial velocity of 105 kt and deceleration initiation at approximately 1 nmi. Glide slope angles of 5 degrees and 3 degrees, respectively, are being derived with an MLS system, and have been checked out in preliminary flight tests. In general, the flight experiment will investigate a limited number of SCAS designs for the AV-8B, using existing control power and actuator authority limitations, in combination with several head-up display formats for each of these profiles with simulated breakout at several range/altitude points. The flight experiment is of fairly limited scope ($\sim$ 20 hours), and so ground simulation using the X-22A ground simulation facility is being employed both as a design tool and to expand the data base.

As an example of one aspect of this ground simulator experiment, Figure 22 shows a hierarchy of Task IV head-up display formats based on modifications to the proposed AV-8B HUD presentation. In addition to the general characteristics shown, optional attitude presentations and velocity read-outs are also being investigated. Other aspects of the preliminary experiment include over 150 evaluations of various longitudinal and lateral-directional SCAS designs to provide a rational range of characteristics for the flight experiment.

It is clear that the X-22A research facility provides an unmatched capability for performing future research in this area; possible examples include guidance, display, and control requirements to permit zero-zero shipboard VTOL landings, or similar requirements for VTOL, STOL or conventional aircraft using projected Microwave Landing Systems (MLS). The X-22A's unique combination of variable stability/control dynamics and variable display capabilities, coupled with the increased efficiency of flight time usage afforded by the ground simulator capability and the digital data processing system, results in a versatile and extremely useful research tool for these investigations.

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GENERAL SPECIFICATIONS

DIMENSIONS

Length	39.57 ft	
Height	20.69 ft	
Tread	8.0 ft	
Wing	Front	Aft
Area	139 sq ft	286 sq ft
Span	22.97 ft	39.24 ft
Aspect Ratio	3.86	5.38

ENGINE RATINGS

SHP	SLS	Thrust	rpm	Min.
1250	Mil.	154	19,500	30
1060	Nor.	132	19,500	Cont.

POWER PLANT

No. & Model	(4) YT58-GE-8D
Mfr.	General Electric Co.
Type	Free Power Turbine
Reduction Gear Ratio	0.133
Prop Mfr.	Hamilton Standard
Prop. Dia.	84 in.
No. of Blades	3
Tail Pipe	Fixed Area

WEIGHTS

Loading	lb
Empty	11,622
Gross	15,287
Max Takeoff	18,420
Max Landing	15,287

FUEL

No. Tanks	Gal	Location
1	465	Fuselage

Fuel Grade JP-4 or JP-5

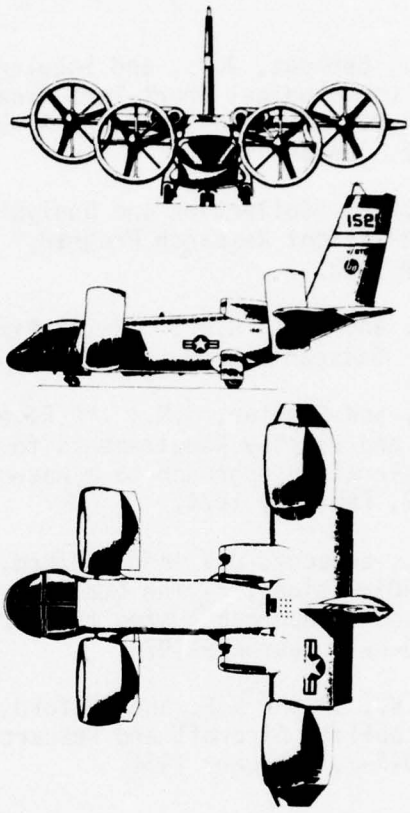


Figure 1 X-22A Aircraft, 3 View

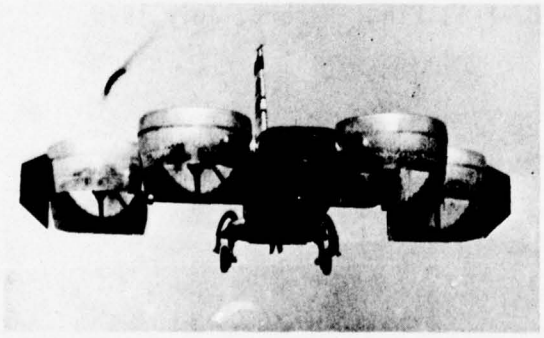


Figure 2 X-22A in Hovering Flight

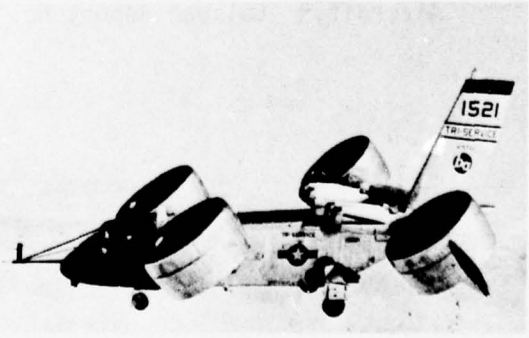


Figure 3 X-22A in Forward Flight



Figure 4 Microwave Landing System

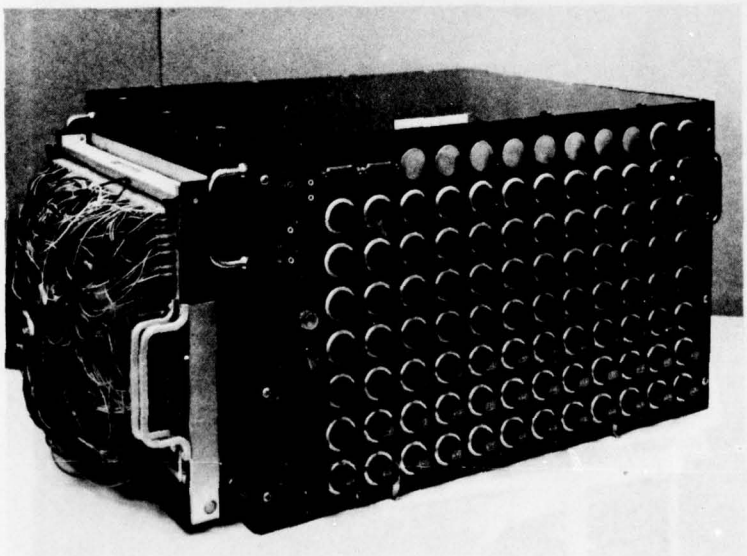


Figure 5 Airborne Analog Computer

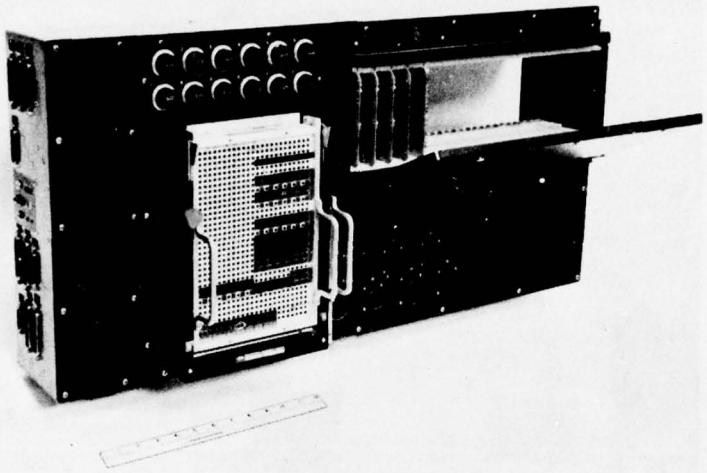


Figure 6 Airborne Systems Interface Unit

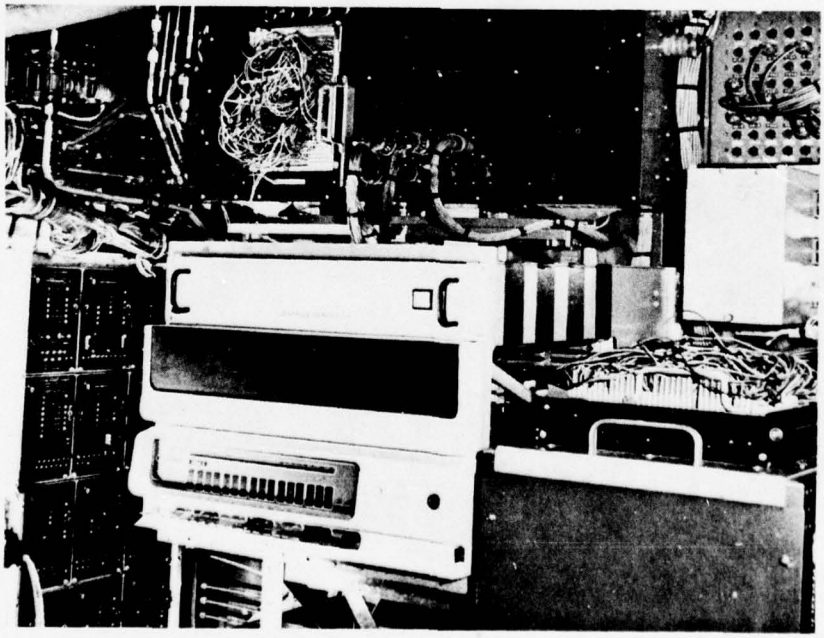


Figure 7 Programmable Digital Display Equipment



Figure 8 Cockpit Computer Terminal

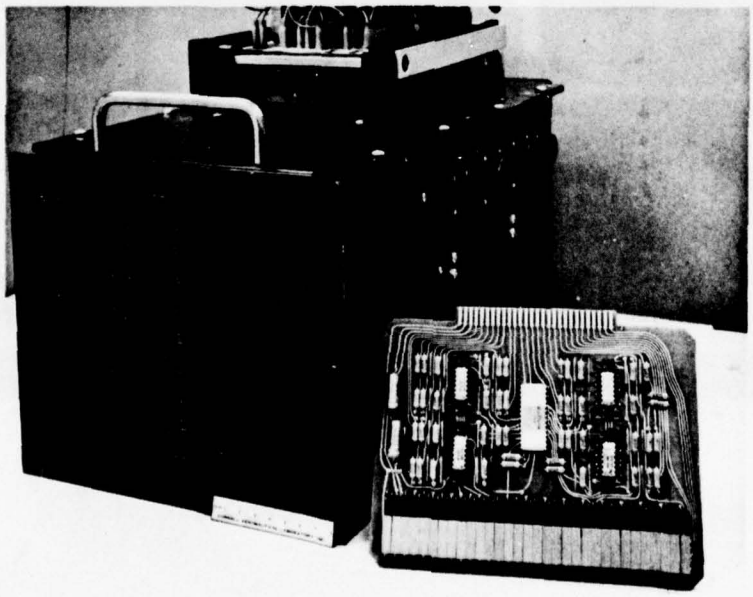


Figure 9 Programmable Analog Symbol Generator

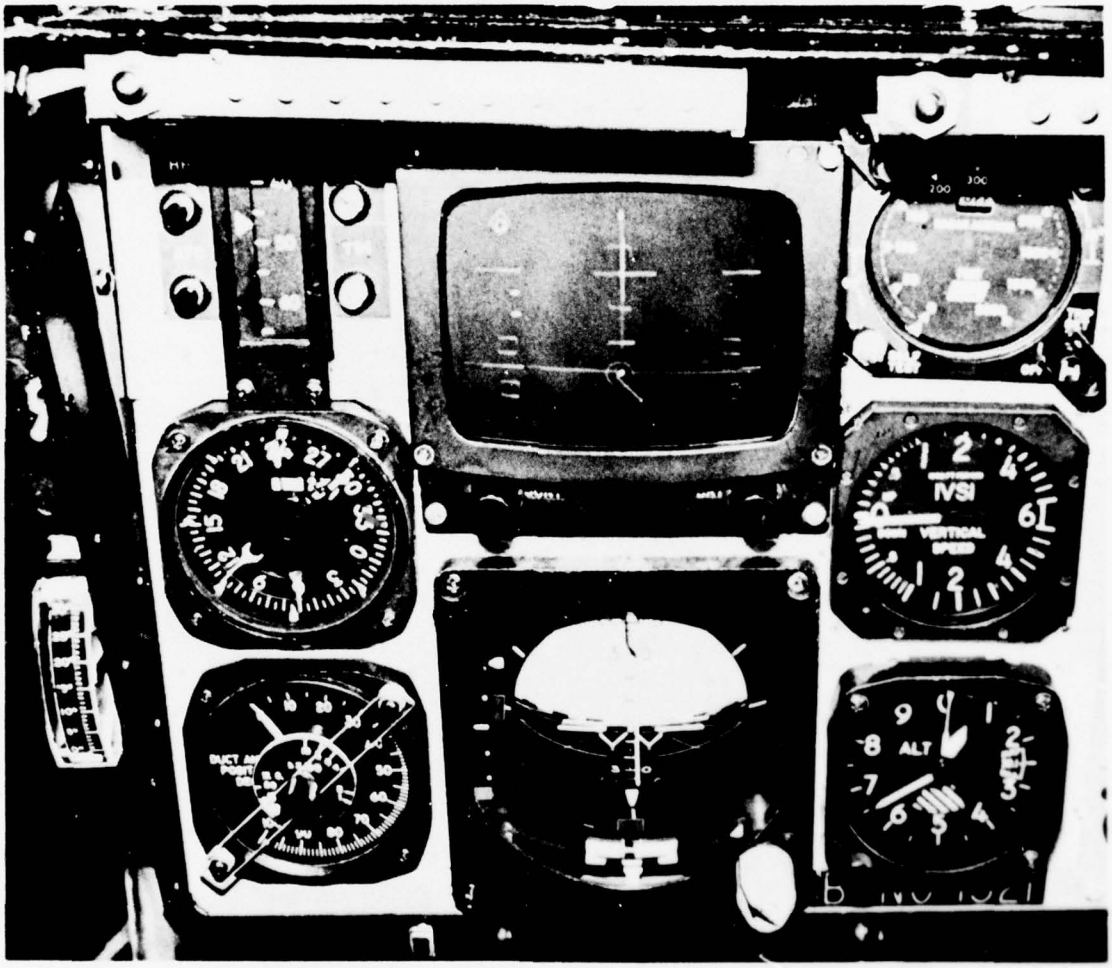


Figure 10 Head-Down Display

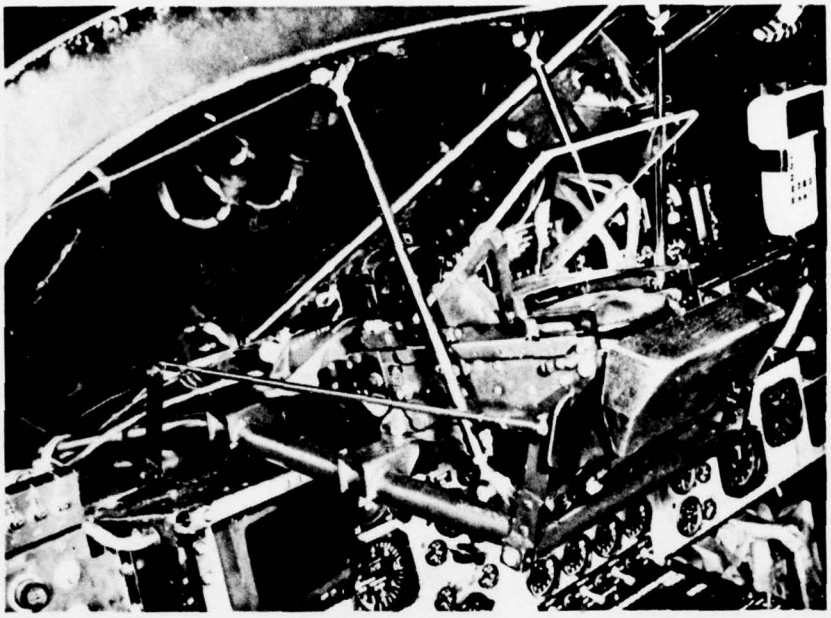


Figure 11 Head-Up-Display - Viewing Position

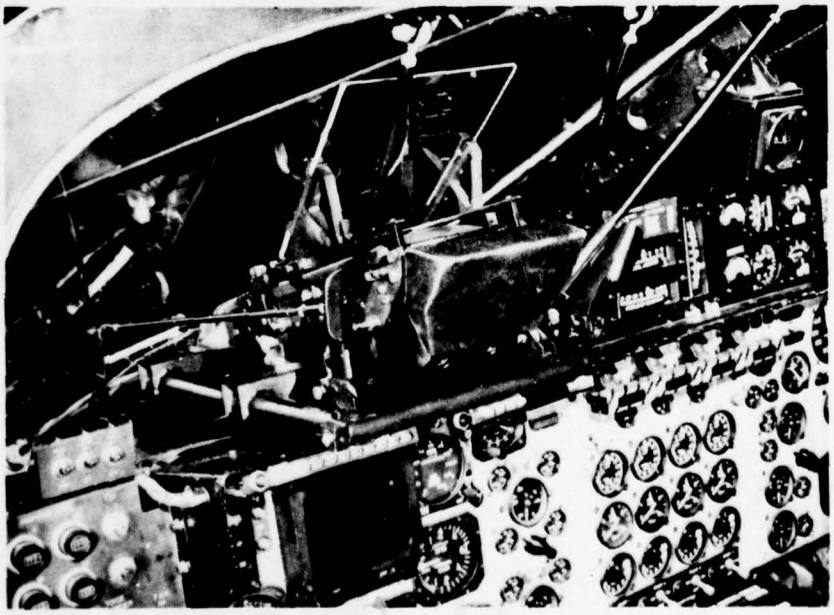


Figure 12 Head-Up-Display - Retracted Position

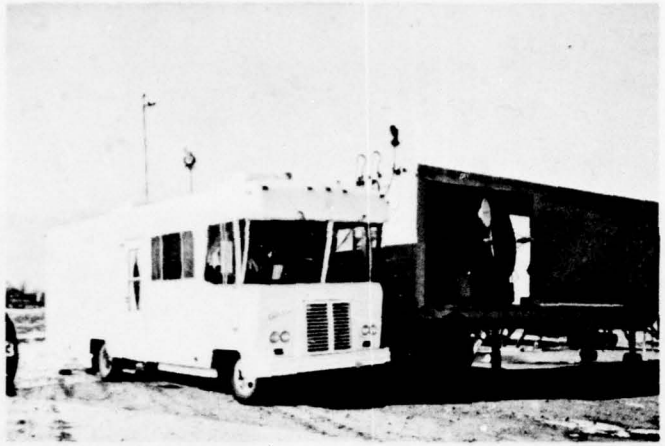


Figure 13 Telemetry Van (Alongside AN/SPN-42T1 Radar Van)

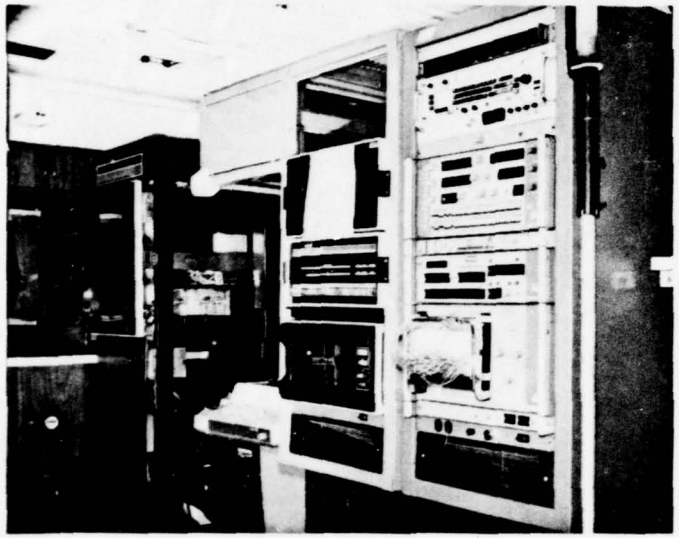


Figure 14 Telemetry Van, Internal View (Looking Aft)

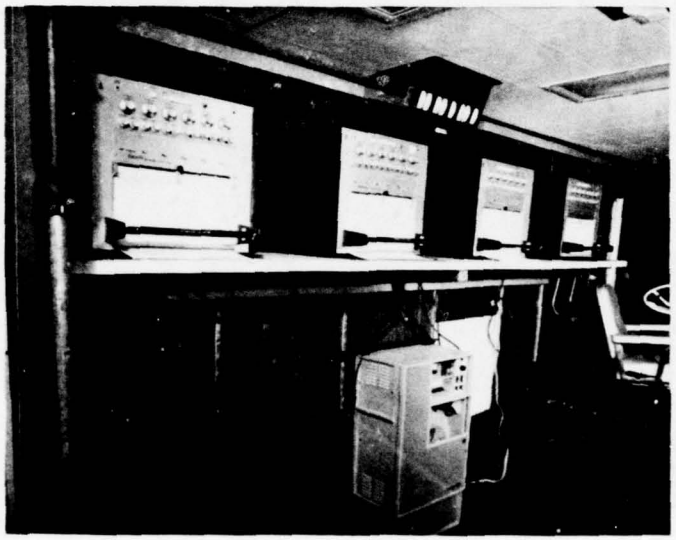


Figure 15 Telemetry Van, Internal View (Looking Forward)

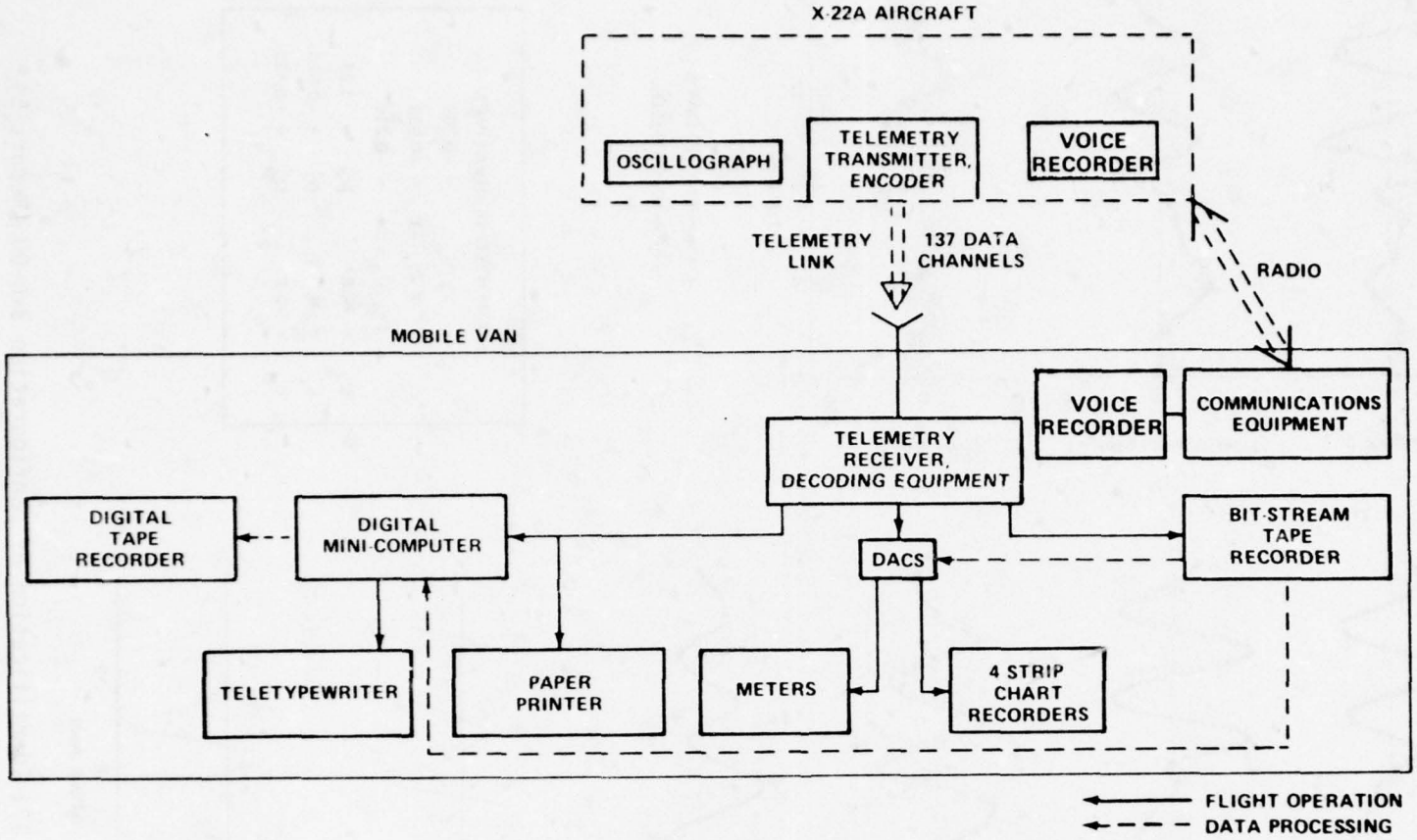


Figure 16 Schematic of Digital Data Acquisition System

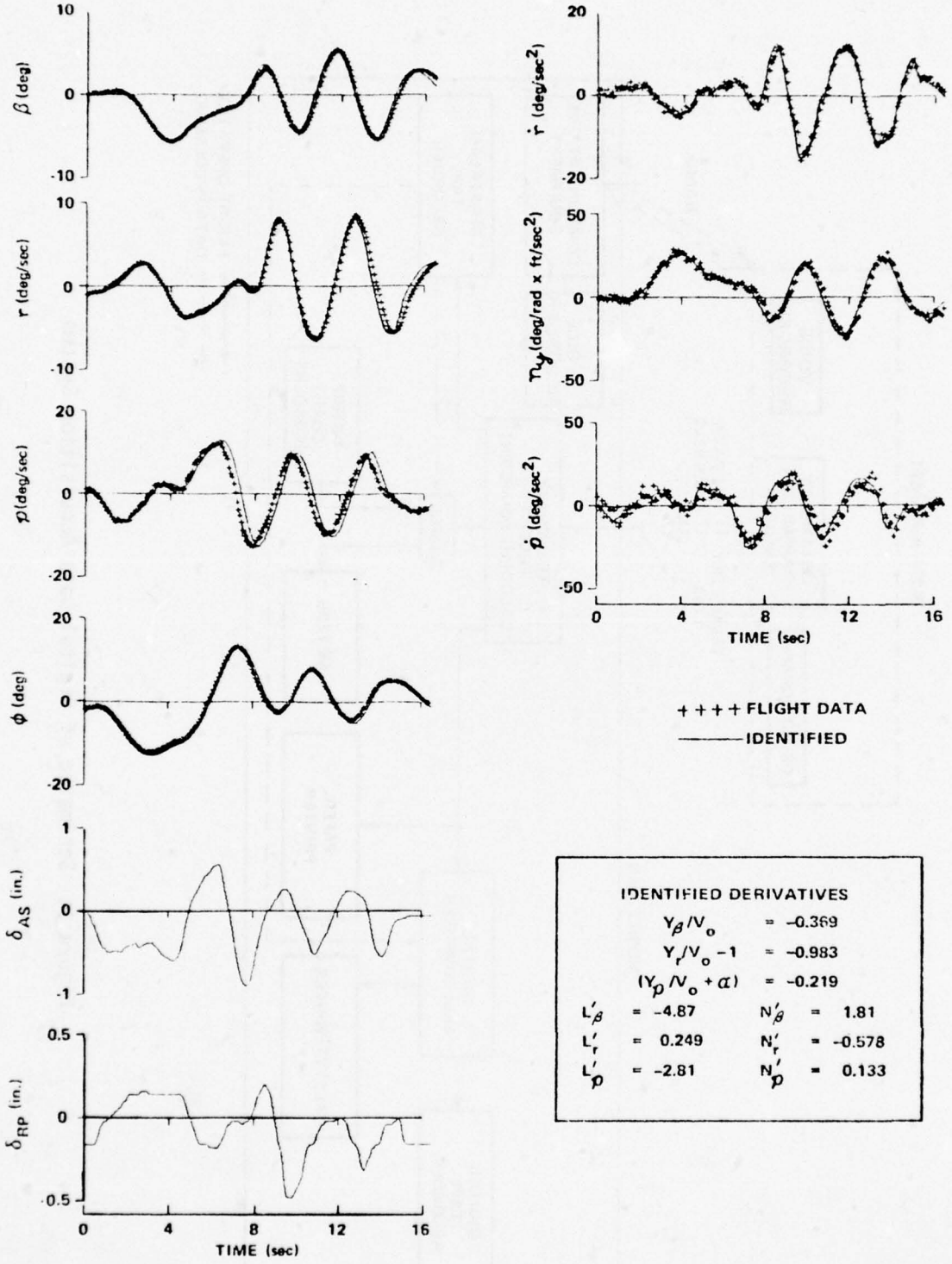


Figure 17 Identification of Configuration 3-0-00 (Report 5)

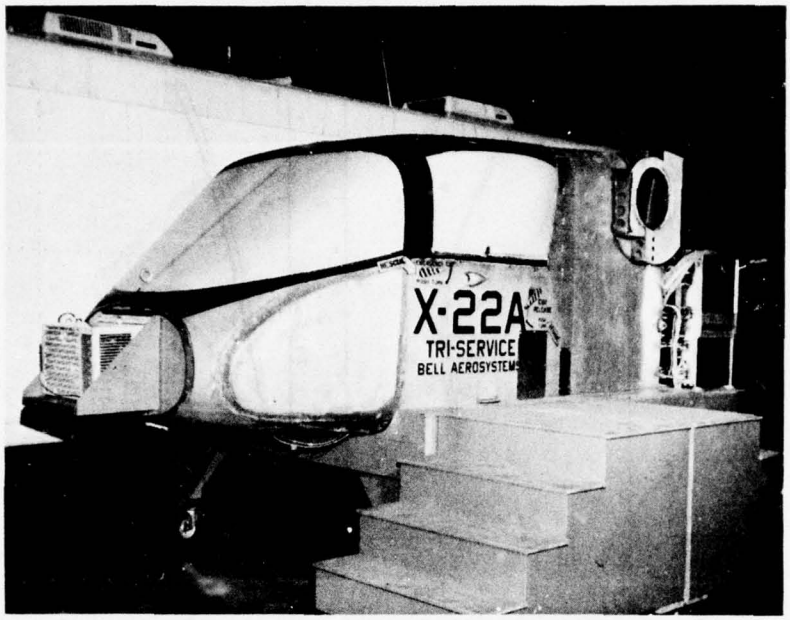


Figure 18 X-22A Ground Simulator

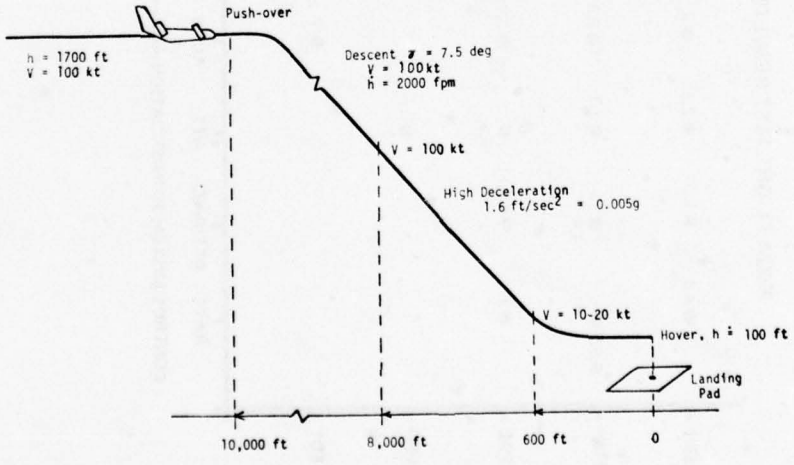


Figure 19 Decelerating Descending Transition Landings on Instruments

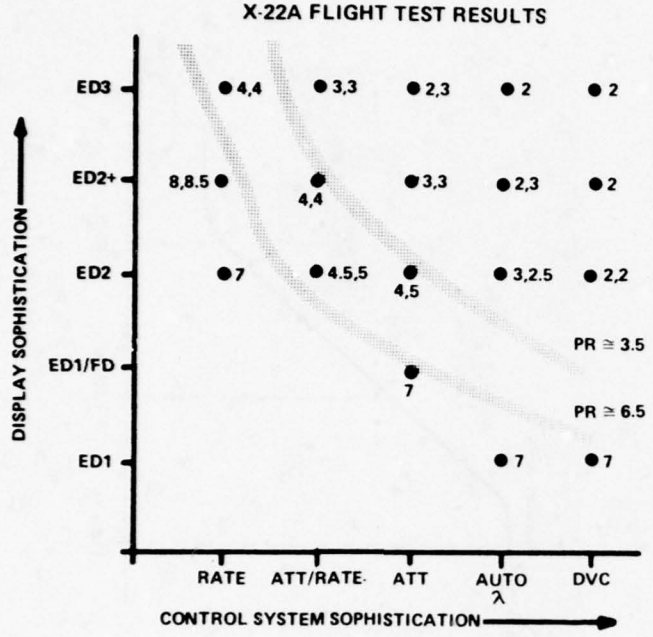


Figure 20 X-22A Task III Flight Test Results (Cooper-Harper Pilot Rating (PR) Data

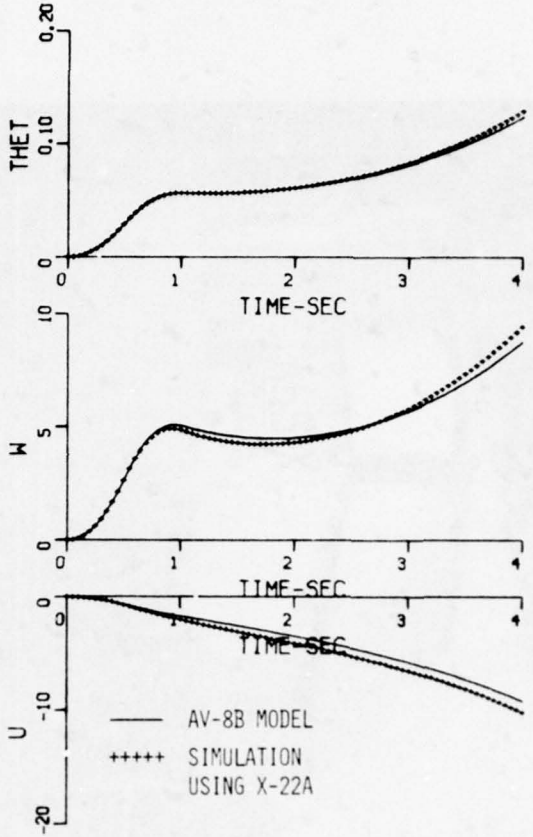


Figure 21 65 kt Longitudinal Simulation of Av-8B

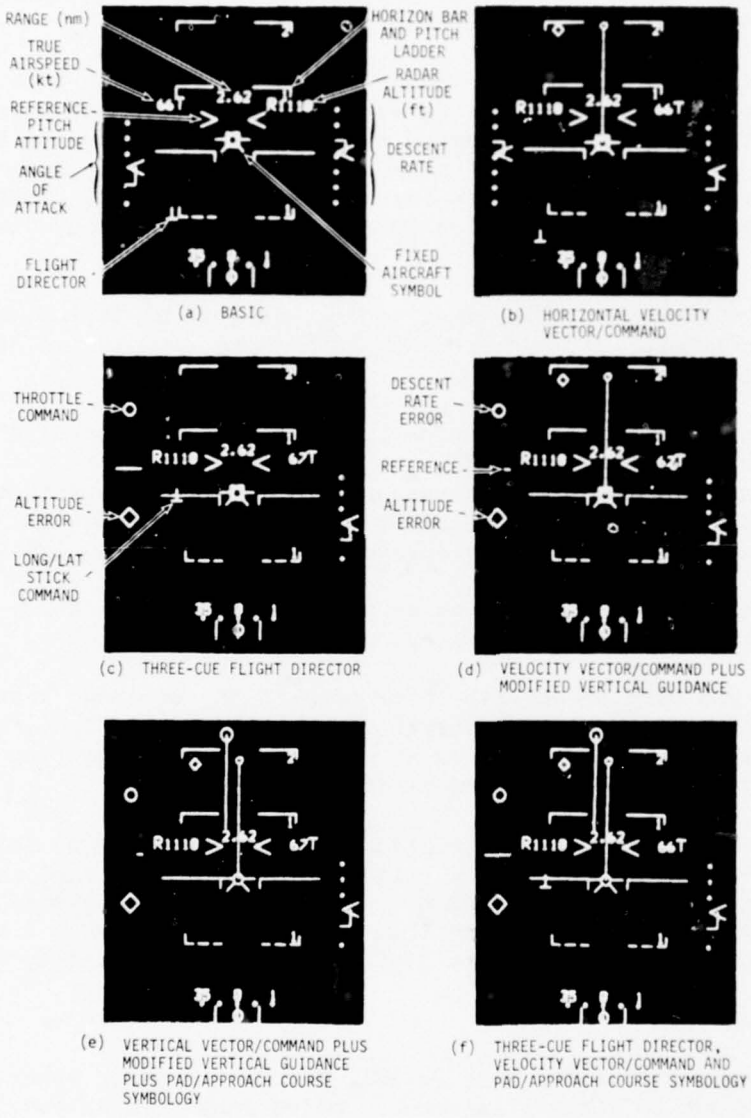


Figure 22 Basic/Modified AV-8B HUD Formats

DISCUSSION

G. Robert Flynn: I have a question, really, for the first speaker. When you hardened the Nova, did you do anything other than stiffen up those big, floppy P.C. boards? And, if so, what's your assessment of the practicality of retrofit hardened vs. buying your own?

Bielman: We changed a lot of nuts and bolts type of hardware throughout the Nova such as installing lock washers, elastic stopnuts and things like that. The rest of the effort consisted of attempts to stiffen up the floppy printed circuit boards and then we've shock mounted the whole assembly. Now it'll take some flying experience to see if that did the job. That's one milestone we haven't passed yet which is the actual use of the system in flight.

LTCOL Bud Iles: On your profiles that you're going to be flying, are you going to look at lateral air corrections at the same time you're looking at descending/deceleration tasks?

Clark: Starting with the lateral offset? You mean that kind of thing?

LTCOL Iles: That is correct. It'll have a big impact on your test results, I can tell you that right now. The other one was thrust to weight ratio: are you going to limit yourself to representative thrust to weights?

Clark: It'll be the AV-8B as best as we can simulate on the X-22. So it'll be AV-8B thrust to weight ratios.

LTCOL Iles: Do you have an ability to program in any envelope restraints that are going to be probably applicable to the aircraft? Alpha, beta, dx/dy restraints? Are you just going to prevent them from getting into it or are you going to actually program it into your HUD?

Clark: There's no plan right now to program it into the HUD on this current experiment. We're really limited in flight hours in the current experiment; in fact, we're stretching the flight hours we have just to investigate what we are investigating. But the capability of investigating such a thing on the X-22 is certainly there with the digital programmable display we now have.

LTCOL Iles: Thank you.

Bielman: And, Bud, I'm pretty sure we will have a side step maneuver as part of our breakout to a final approach. We've done this in past programs.

Hal Fluk: Have you in the past or do you intend to investigate descent rates steeper than 12^{o}?

Clark: Right now we have no intention of investigating them. I don't think we've ever gone beyond 12^{o} in the past. Correct me if I'm wrong.

Bielman: Twelve degrees is about as high as we've gone based on avoiding flow separation in the ducts.

Fluk: That's what's limiting you?

Bielman: Well, it depends on the speed, too, of course, but when you get up around 1800 feet a minute vertical descent rates, it begins to become a problem.

Fluk: O.K.

Daniel Cichy: As far as future use of the X-22, do you plan any looking at the ship integration problem?

Bielman: We've got a problem. We'd like to do that certainly, but we've got just a pure physical problem of getting the X-22 on board a ship and getting a decision in first place whether or not it is ship compatible. So I doubt very much, as it looks right now, that we will.

A PILOTED SIMULATION OF VTOL LANDINGS ABOARD A NON-AVIATION SHIP

RONALD M. GERDES
NASA-AMES RESEARCH CENTER

INTRODUCTION

The Navy is now firmly committed to fleet-wide V/STOL operations. One of the more demanding tasks that the fleet V/STOL pilot faces is that of performing a precision decelerating approach and vertical landing to a platform at sea. The high pilot workload associated with this maneuver has been well identified within the helicopter community and more recently with the advent of the AV-8 Harrier.

Ames Research Center embarked upon a series of lift-fan research aircraft simulations about six years ago to examine V/STOL handling qualities and operational problems. One objective was to find solutions to these inherently high pilot workload problem areas. The last simulation concluded with an evaluation of terminal guidance and control to a landing on a non-aviation ship.

This paper will discuss the major results of that simulation from a pilot's point-of-view. Time does not permit detailed discussions of the simulation setup or aircraft description and modeling. The objective will be to discuss the relative merits of three important aspects of the lift-fan simulation program - results that show promise in reducing pilot workload during V/STOL aircraft recoveries at sea.

The pilot's task consisted of performing a series of precision decelerating approaches to a frigate-sized ship with major emphasis on the evaluation of three piloting aids: (1) an advanced attitude control system, (2) a decoupled flight path control system and (3) an integrated head up display (HUD). It is hoped that I can give you a glimpse of "things to come".

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DESCRIPTION OF THE AIRPLANE

The simulated airplane was the McDonnell Lift/Cruise Fan V/STOL Research Technology Aircraft which weighs about 28,000 lbs (Fig. 1). It is powered by three turbojet engines which gas drive three fans, one of which is a lift-fan located in the forward fuselage. The exhaust nozzles of the lift/cruise fans are deflected to change thrust vector. The thrust from all three fans can be deflected for lateral translation and yaw control. Pitch and roll moments are generated by differential fan thrust in the V/STOL regime. Stability and control augmentation is described later under "piloting aids".

DESCRIPTION OF PILOTING AIDS

The piloting aids described below have evolved as a result of pilot opinion data collected during the lift-fan research simulation series. Details of the theory of operation, math modeling and mechanical implementation are beyond the scope of this discussion and are contained in References 1 and 2. The description will be limited to basic control functions and how they are used by the pilot.

ATTITUDE CONTROL SYSTEM

A summary of the attitude control system modes is presented in Fig. 2. Each axis has been optimized for both the hover regime (below 20 kts) and for the transition range (from 30 to 200 kts). Simulation results indicated that for hover maneuvering, pilots prefer attitude command (proportional to stick deflection) for the pitch and roll axis along with rate command plus heading hold for yaw. Pitch attitude command is retained throughout the transition speed range while the roll axis reverts to a roll rate command plus bank angle hold mode at speeds above 30 kts. The heading hold loop is also removed from the yaw axis at the same time. The roll and yaw axes are gradually switched between the hover and transition regions (20-30 kts) with a blending technique.

DECOUPLED FLIGHT PATH CONTROL SYSTEM

Basically, this sytem is a power management control that allows the pilot to independently control the horizontal and vertical flight path velocity (or acceleration) components without coupling effects. This decoupling of the vertical and horizontal flight path axes reduces pilot workload to a great extent.

Along with the conventional throttle and thrust vector angle controls is added a flight path controller which is operated by the left hand. The fundamentals of control are shown in Fig. 3 for the translational rate and the transition (landing approach) modes of flight. Movement of the controller handle fore or aft of a detented mid point commands pure vertical velocity (up or down) for both modes of flight. A thumb wheel, located on the inside of the controller handle (Fig. 3(b)) is used to command horizontal acceleration. Rolling the wheel fore or aft from a detented "zero" position commands acceleration in proportion to displacement. Controller servo logic commands coordinated combinations of thrust level and vector angle to produce the decoupled-commanded (horizontal and vertical) component values. Lateral flight path displacement is controlled through bank angle change in the conventional manner. Flight path velocities and accelerations are inertially sensed and controlled.

A hover translational rate mode is automatically phased-in between 30 and 20 knots. An omnidirectional thumb button ("coolie hat"), located on top of the controller handle (Fig. 3(a)) commands inertial vector velocity in the horizontal plane in proportion to thumb force and direction. Aircraft pitch, roll and yaw attitude are held fixed with hands and feet off the controls.

It should be pointed out that the cockpit throttle and thrust vector controls are moved by power servos that respond to flight-path control system commands (see Fig. 4). The pilot can thus monitor servo inputs (as in the case of a conventional auto-throttle system) and take over manually in the event of a malfunction. The flight path controller modes are summarized in Fig. 5.

HEAD-UP DISPLAY

The HUD was also developed in an evolutionary manner to suit piloting tasks. The finalized symbology content was based on having all required flight information displayed "heads up". Thus to some, the first impression is that it is "too cluttered".

HUD symbology is shown in Fig 6. Pitch and roll attitude are visualized by relative movements of the pitch ladder with respect to the fixed airplane symbol. Bank angle is depicted digitally above the airplane symbol. The heading tape is located at the top of the display, and includes a side-force "ball" symbol. Horizontal acceleration and vertical velocity scales are on the left and right sides of the display with moving "carrot" symbols (>) to indicate values. Other digital information shown are thrust vector angle and engine RPM (top of display) and values of horizontal velocity, longitudinal distance to go, lateral offset and altitude above the landing platform. With respect to velocity, the upper value shown is actual and the lower one is commanded. A pitch attitude trim symbol (▷ ◁) shows commanded pitch trim position. A "rising runway" symbol appears below 50 feet. A velocity vector symbol (⊗) shows flight path angle, angle of attack and side slip angle.

A ship landing platform symbol automatically appears when within a horizontal range of 500 feet. This symbol also rotates in a plan-view perspective to indicate ship's relative heading.

Flight director information, derived from the onboard computer, is displayed in terms of roll attitude and flight path controller commands. Roll attitude command is represented by vertical needle displacement. Horizontal deceleration scheduling is commanded by a director bar symbol (▬) on the acceleration scale, while vertical velocity scheduling is commanded by a similar director symbol on the vertical velocity scale. The pilot responds to flight path director commands by moving the appropriate control in such a manner as to "track" the director bars with the pilot command symbols (▷ and ◁).

The pilot is aided in performing the hover maneuvering task of translating over to the platform and landing. Two horizontal velocity vectors are provided: pilot commanded velocity vector and airplane velocity vector. The command arrow head (—▷) is placed over the platform center and held there while airplane velocity is monitored (——→). The "rising runway", vertical velocity and absolute altitude aid in performing a precise touchdown.

AUTOMATIC LANDING SYSTEM

The integrated system has a fully zero-zero automatic approach and land capability. Approach monitoring is carried out through reference to HUD director, command and situation information.

DESCRIPTION OF THE SIMULATOR

The Ames Flight Simulator for Advanced Aircraft is a six-degree-of-freedom moving-base simulator. The cockpit layout (Fig. 7) is conventional except for the addition of the flight path controller. The visual scene and HUD interface are generated by closed-circuit television techniques. A close-up of the frigate-type ship model is shown in Fig. 8. The approximate dimensions of the landing platform are 40 ft wide and 60 ft long with a 20 ft diameter circle. (Aircraft dimensions are: 44' wide and 52' long).

PILOT TASKS

Piloting tasks consisted of a series of decelerating precision approaches under a variety of daylight conditions including curved approaches to a moving ship in turbulent crosswinds under IFR conditions. System failures were also evaluated. Ship motion was programmed up to a sea state of 4. Test pilots representing

the aircraft contractor, the Navy Department and NASA-Ames participated in the evaluation. Both curved and linear approaches of varying steepness were evaluated. This discussion is limited to the more difficult to perform curved case.

A typical curved approach profile for a 6° initial glide slope is shown in Fig. 9. Initial conditions were set up at 2,200' at 120 kts on glide slope and displaced 500' from the localizer to introduce a lateral tracking task. The pilot was asked to follow director commands which tracked the vertical and horizontal deceleration profile shown in the figure. He was also asked to track over to the localizer by responding to the lateral flight director commands. This procedure was followed on down until a hover was established at 50 feet above the landing platform - 100 feet aft and 100 feet right of center (see Fig. 8). The hover translational rate mode was phased in between 30 and 20 knots. The aircraft was then "slid" over to the center of the platform where a descent rate was established until touchdown.

RESULTS OF THE EVALUATION

The overall handling qualities looked good from the beginning of the approach at 120 kts to hover touchdown. Turbulent crosswinds presented no particular problems. The decoupled controller provided precise control of horizontal deceleration (speed control) and vertical descent rate while the high gain attitude loops masked most of the external attitude disturbances resulting in a comfortable workload task. The pitch attitude trim and display (HUD) feature was excellent in reducing pilot workload. Attitude command control was retained in the pitch axis from the initial point to touchdown. Pitch attitude was held constant while speed changes were made with the flight path controller. The pitch trim control was used to make only minor pitch attitude changes. The blending of rate command plus bank angle hold into bank angle command between 30 and 20 knots provided a smooth switchover of the lateral control system with no bothersome transients. Stick inputs were thus minimal - approaching a near "hands-off" condition. The flight-path control system proved to be a great aid in performing the demanding deceleration task. It took time to "proceed up the learning curve" in following the flight director commands, but an effective HUD symbol scan pattern was soon established. Display of both velocity and acceleration along the vertical and longitudinal axes (with respect to the touchdown spot) and the ability to precisely and rapidly control them was the key factor in performing successful terminations to hover. Thus the pilot was able to monitor both horizontal velocity and range to the spot while primarily following the flight director deceleration commands with the thumb wheel controller. Likewise he could monitor vertical descent rate and absolute altitude above the spot while following the descent rate flight director commands with the controller lever. The appearance of the ship symbol in the HUD served to alert the pilot of the approach to the initial hover point. With the stick centered (hands off) and the flight path controller lever and thumb wheel in their zero detents, the aircraft was "locked" into a six degree of freedom hover.

The procedure of translating over to the center of the spot was easy and precise - even in the turbulent crosswind cases. HUD symbology for the precise landing task was excellent and allowed the pilot maximum utilization of flight path control system capabilities. Positioning the aircraft over the spot with translational rate mode was a "piece of cake". Thumb pressure was used to vector the aircraft symbol to the spot with altitude held at 50 feet. The flight path control handle was then moved aft slightly to establish the desired sink rate to the landing platform. The "rising runway" symbol, absolute altitude and vertical rate readouts assisted in judging the touchdown maneuver since the small landing platform was primarily out of view in the simulated visual scene. There was a desire to follow the ship's attitude changes during this task. The HUD however provided an excellent reference with which to judge the effects of ship's motion. It was felt that successful low visibility landings would have been impossible without the HUD.

A VFR situation was represented throughout most of the simulation, however zero-zero (HUD only) approaches were demonstrated with success, and no significant increase in pilot workload was noted. Fully automatic landings were also demonstrated with complete pilot acceptance.

A brief failure assessment was made to evaluate the relative merits of the two (pilot aid) control systems. A series of "manual" approaches was attempted with loss of the flight path control system only and then with both the flight path and attitude control systems failed. The results of this study are presented in Fig. 10 in terms of Cooper-Harper pilot opinion ratings for the entire VFR approach and landing task. A marked increase in pilot workload (or compensation to perform the task) was required with the flight path control system failed (pilot ratings = 5 1/2-6). Major controllability problems were encountered when both systems were inoperative (pilot ratings = 8-9).

CONCLUSIONS

A simulation of a V/STOL non-aviation ship landing task, using a lift-fan research aircraft, was performed to evaluate the relative merits of three piloting aids. The following conclusions were drawn as a result of this investigation:

1. Overall handling qualities and workload level were satisfactory for the entire approach and landing task including turbulent crosswinds and a sea state of 4.

2. The advanced attitude control system masked most of the external attitude disturbances and reduced pilot workload to a near "hands-off the stick" operation. This system was found to be essential for adequate task performance.

3. The decoupled flight path control system was most responsible for the overall reduction in pilot workload. This system was found to be mandatory for satisfactory task performance.

4. The integrated head up display (HUD) provided all of the essential information required to perform the task. The HUD also proved to be an essential part of the piloting aids - allowing the pilot to use the attitude control and flight-path control systems to their maximum capabilities.

5. A fully zero-zero all weather capability was demonstrated with no significant increase in pilot workload.

6. An automatic non-aviation ship landing system capability was demonstrated with full pilot acceptance.

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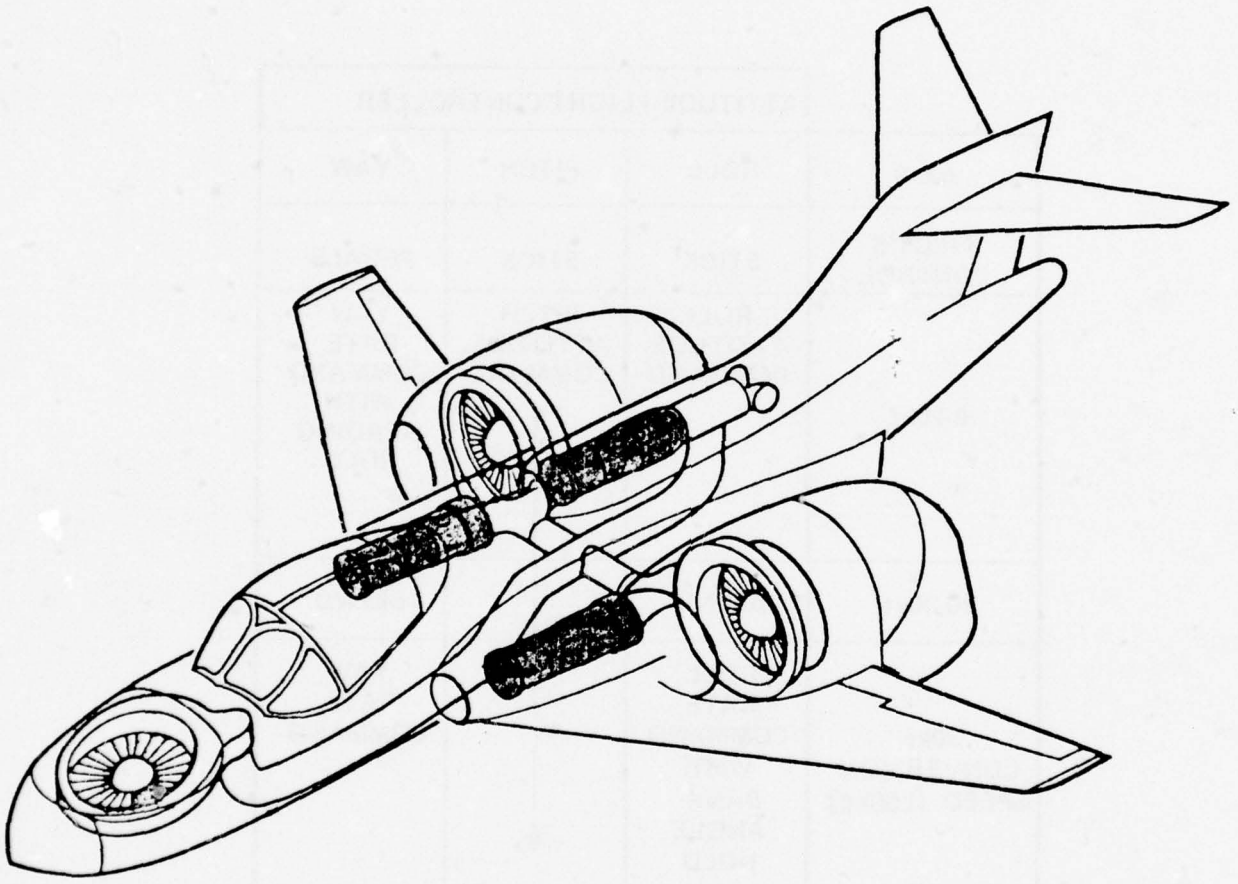
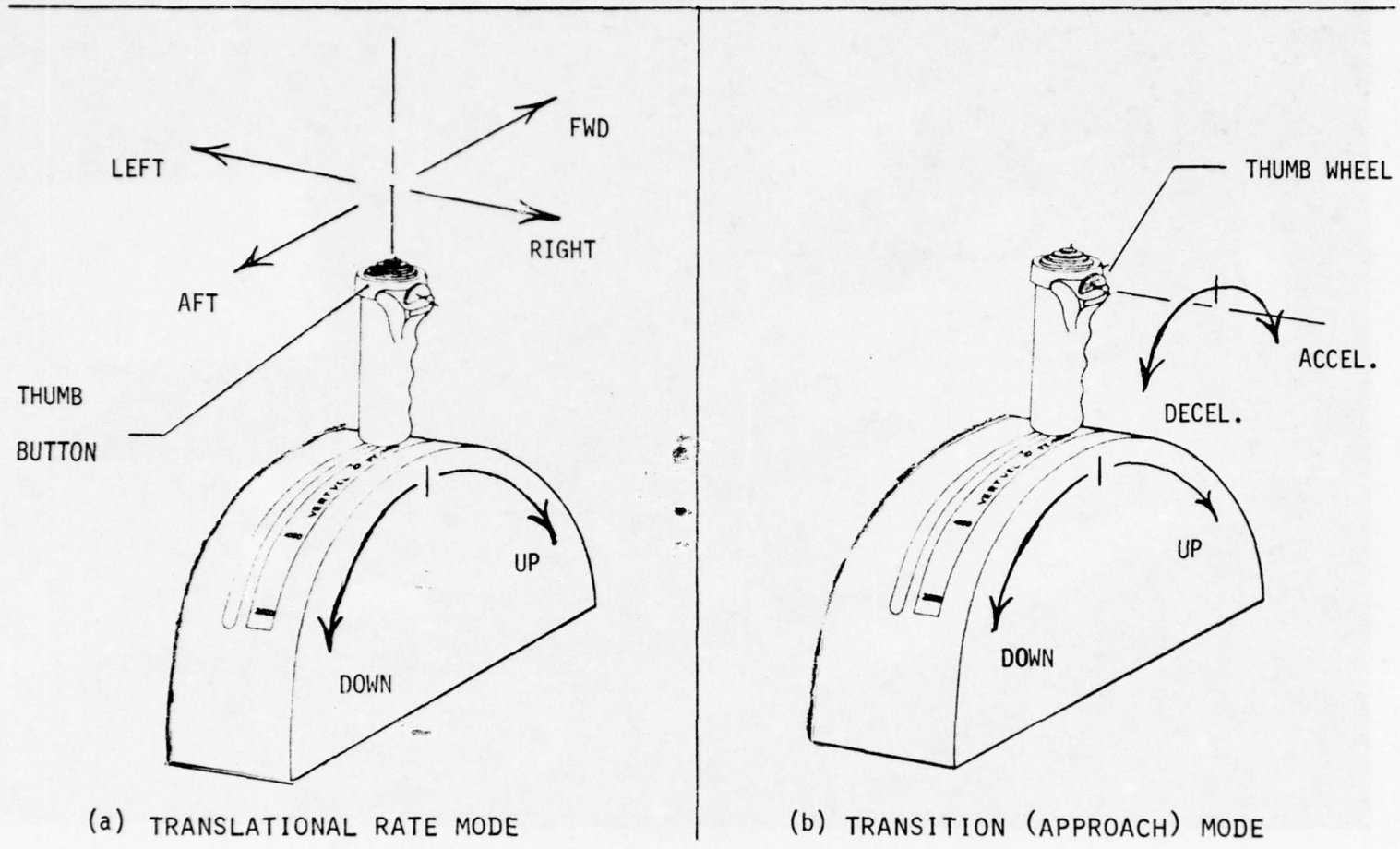


Fig. 1 Lift-Fan Research Technology Aircraft

	ATTITUDE FLIGHT CONTROLLER		
AXIS	ROLL	PITCH	YAW
PILOT'S CONTROL	STICK	STICK	PEDALS
0-20kt	ROLL ATTITUDE COMMAND	PITCH ATTITUDE COMMAND	YAW RATE COMMAND WITH HEADING HOLD
20-30kt	BLEND		BLEND
30kt-CONVERSION SPEED (200kt)	ROLL RATE COMMAND WITH BANK-ANGLE HOLD		YAW RATE COMMAND

Fig. 2 Attitude Flight Controller Modes

DECOUPLED FLIGHT-PATH CONTROLLER



(a) TRANSLATIONAL RATE MODE
(0-20 kts)

(b) TRANSITION (APPROACH) MODE
(30-200 kts)

Fig. 3 Flight-Path Controller Fundamentals

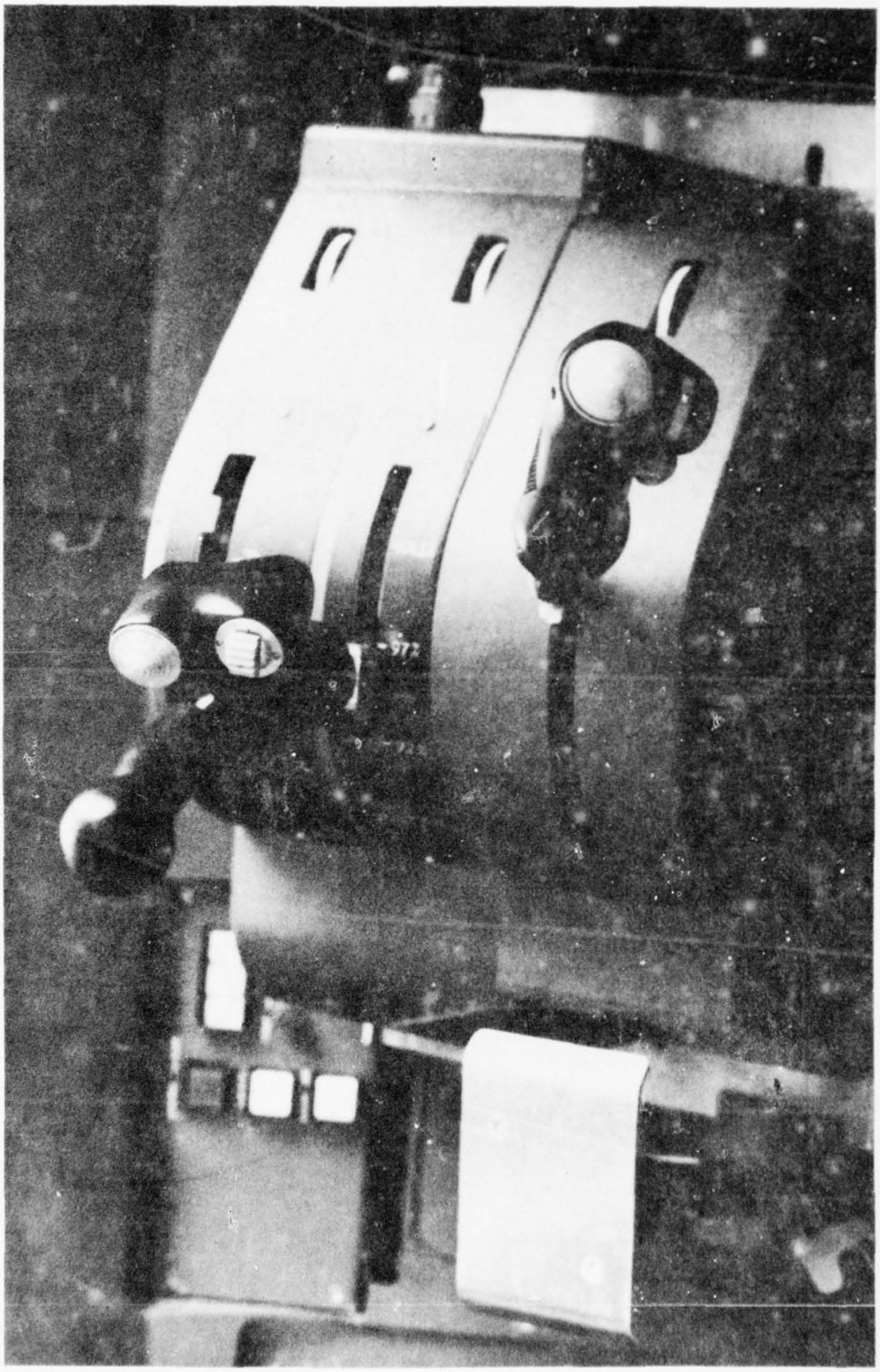


Fig. 4 Power Management Controls

	FLIGHT-PATH FLIGHT CONTROLLER			
AXIS	LONGITUDINAL		LATERAL	VERTICAL
PILOT'S CONTROL	THUMBWHEEL	THUMB BUTTON	THUMB BUTTON	LEVER
0-20kt	ACCELERATION COMMAND WITH VELOCITY HOLD	VELOCITY COMMAND	VELOCITY COMMAND	VELOCITY COMMAND
20-30kt		PHASE OUT	PHASE OUT	
30kt-CONVERSION SPEED (200kt)				

Fig. 5 Flight-Path Controller Modes

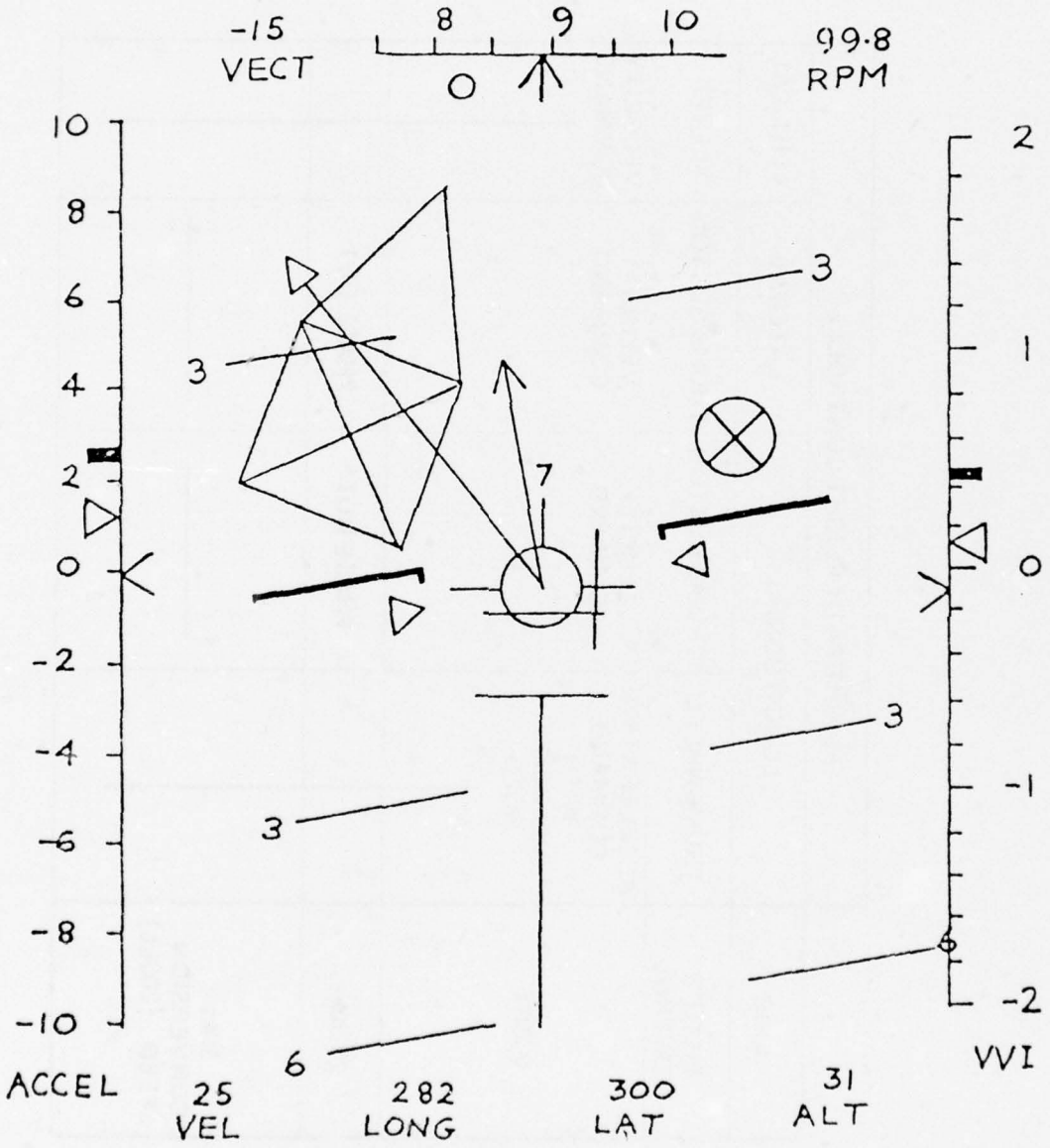


Fig. 6 Head-up Display Format

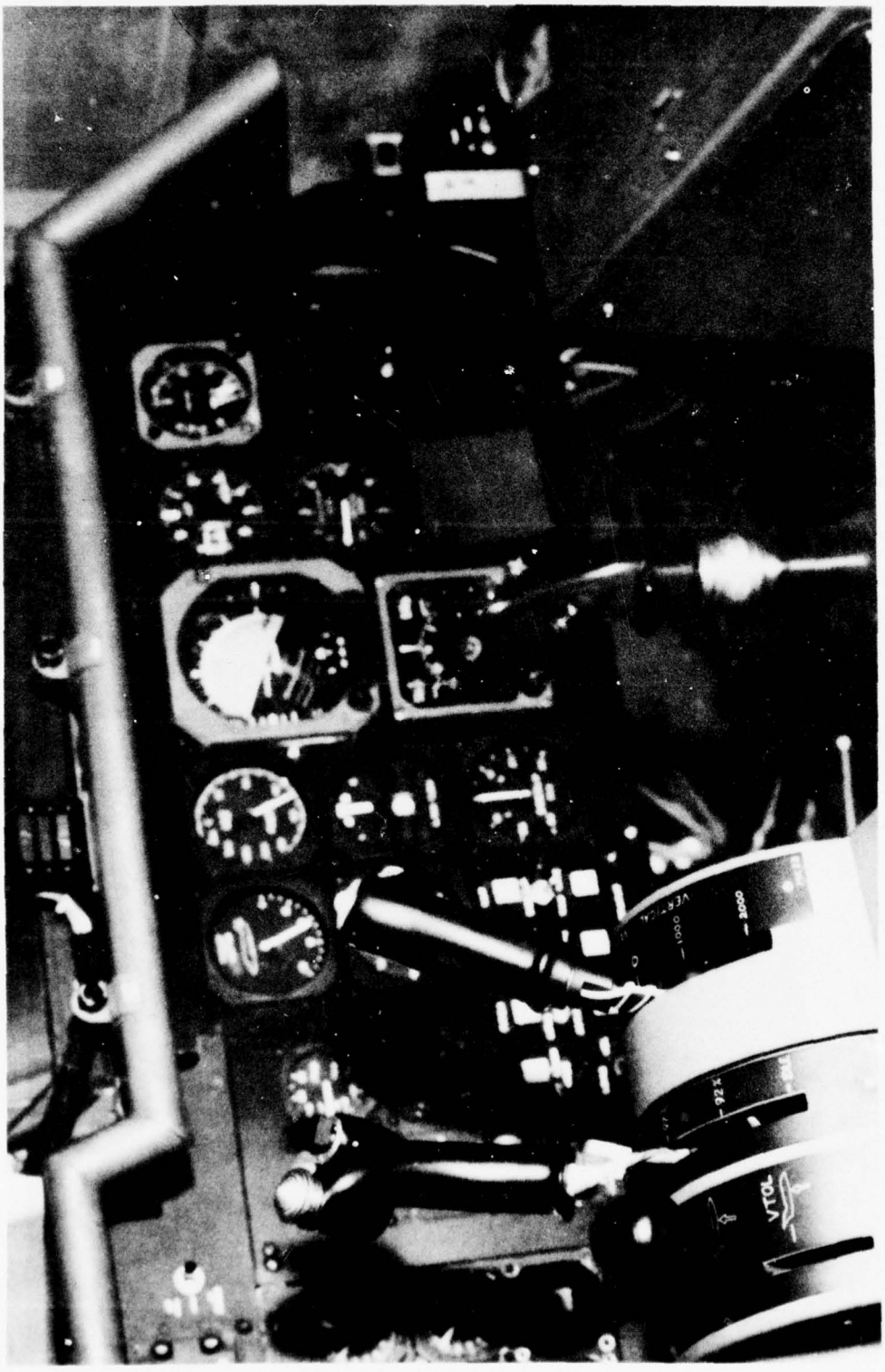


Fig. 7 Simulator Cockpit View



Fig. 8 View of Ship From Initial Hover Point

TYPICAL APPROACH PROFILE

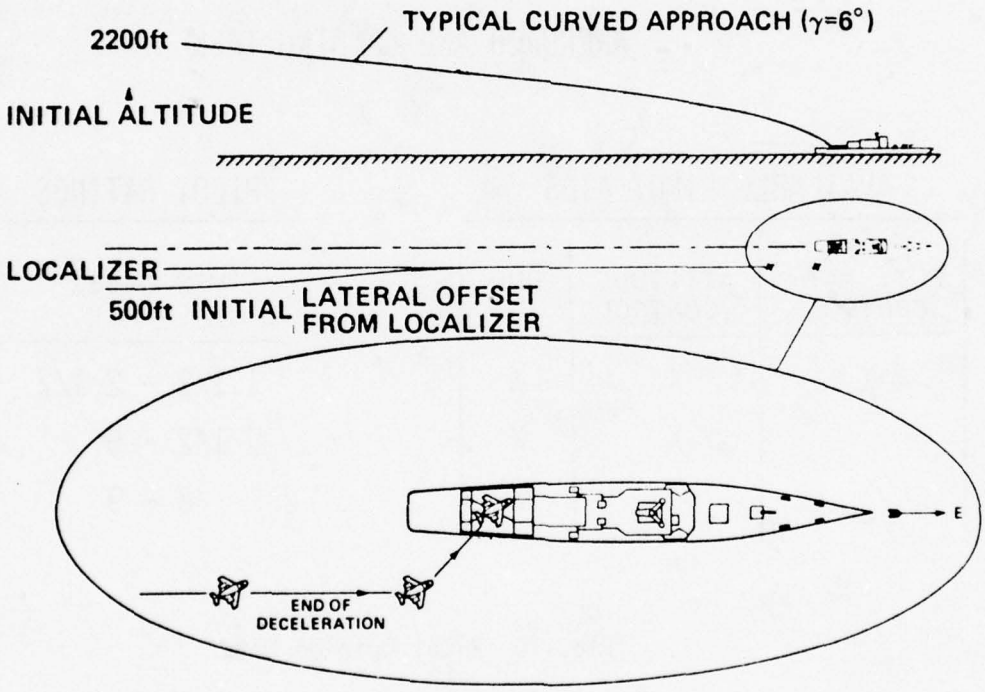


Fig. 9 Typical Approach Profile

NON-AVIATION SHIP

APPROACH AND LANDING TASK

AVAILABLE PILOT AIDS			PILOT RATINGS
FLT. PATH CONTROL	ATTITUDE CONTROL	HUD	(VFR CASE)
X	X	X	1 1/2 - 2 1/2
	X	X	5 1/2 - 6
		X	8 - 9

Fig. 10 Pilot Opinion Data

DISCUSSION

Robert Ringland: Ron, I have one question. You spoke of the velocity speed presented on the head-up display. Were these inertially referenced velocities?

Gerdes: Yes.

Ringland: These task angles had nothing to do with what the wind was doing.

Gerdes: These are inertial velocities with respect to the touch down point. So we don't look at air speed. Bob.

Robert Fortenbaugh: Concerning simulation: what did you use as an airplane model and did you simulate ground effect when you got over the edge of the deck?

Gerdes: What did we simulate as an airplane model?

Fortenbaugh: No, did you simulate ground effects when you got over the edge of the deck?

Gerdes: No, no interface turbulence around the ship was used.

V.K. Merrick: It's the standard Dryden model all the way down and there's no aircraft interface effect.

Gerdes: Standard Dryden model. Gentleman next to Vern back there.

Rich Niemczyk: What sort of guidance systems were used to get your information up to the airplane and what's the accuracy?

Gerdes: Vern will have to answer that also. The accuracy of the guidance system and what kind of guidance system.

Merrick: There was no thought into how you're going to obtain any of this information, just the assumption that it's going to be provided somehow. This was just a study on the use of advanced control systems and how to display them.

Gerdes: O.K. Don't laugh because what did Jack Beilman just say about the little box he has in the back of X-22? Plus or minus 13 feet? He's bragging about how good it works. That's on the ship. That's what we use.

Merrick: No instrument errors were allowed.

Gerdes: No instrument errors were allowed. Any other questions? Thank you.

THE STO DECK LAUNCH PROBLEM

O P Nicholas

Royal Aircraft Establishment Bedford UK

1 PREAMBLE

RAE Bedford has a V/STOL research programme of flight, simulator and theoretical studies stretching back many years. Aircraft have been the Rolls Royce Flying Bedstead, Short SCI and Harrier. Recent programmes have included:

(a) VIFF (Thrust vectoring in forward flight). This was part of a joint research programme with NASA Langley. RAE managed a Harrier flight programme to study the use of VIFF in mock air combat and ground attack and to measure the aircraft's performance characteristics with nozzles deflected. This item may not fall directly under the heading of V/STOL but illustrates benefits that may be associated with a VTOL capability.

(b) 2 seat Harrier control and display research aircraft. This aircraft now flying at Bedford, is fitted with programmable HUD, flexible analogue auto-stabiliser, microwave guidance from prototype MADGE or guidance from lock-follow radar plus data link, and blind-flying screens in the rear cockpit. The airfield has also been equipped with various experimental approach lighting aids.

(c) Simulator. The FS1 No 1 simulator, with three degree of freedom motion, is being used to supplement the flight work on the 2 seat Harrier. At present it is not capable of representing lighting aids but is used for IMC and day operations in low visibility. It has the same HUD as the aircraft, so is valuable for checking out HUD programmes before flying them in the aircraft.

(d) Sea Harrier. Much of the recent work with the Bedford 2 seat Harrier and simulator has been directed towards the Sea Harrier low visibility recovery. We believe that it should be possible to operate down to the specification limits on decision height and visual range without requiring the pilot to initiate transition to jet-borne flight until he has visual contact with the ship.

(e) Hermes Trial. Four Harriers flew from HMS Hermes during a two week trial early this year, primarily to assess launch and recovery aspects of Sea Harrier operation. The Bedford 2 seater flew as part of its continuing programme, two single seaters operated by Boscombe Down took part as outlined in John Williams' paper, plus a 2 seater operated by HSA. All except the last aircraft were fitted with recording instrumentation. The standard Harrier has a separate nozzle-angle lever in the cockpit, so the pilot cannot control

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thrust magnitude and direction simultaneously. However, the HSA aircraft was fitted with an experimental 'speed trim' or 'nozzle nudger' system which gave the pilot limited control of nozzle angle through a thumb switch on the throttle lever. This arrangement was considered to ease substantially the task of coming to the hover in formation with the ship. For the period of the trial Hermes was fitted with a Bedford design experimental approach lighting system and with prototype MADGE microwave guidance equipment to support the research two seater.

(f) Further V/STOL Simulation at Bedford This Year. One of the conclusions from the Hermes trial was that the preliminary recovery simulation and flight work at Bedford had been validated. We are now planning further simulation, primarily to assess revised Sea Harrier HUD displays with particular emphasis on guidance aspects of recovery. We shall also investigate modifications to the existing pitch auto-stab law aimed at improving handling during the recovery.

(g) Further 2 seat Harrier Flying at Bedford This Year. The aircraft's continuing research programme is linked with the simulation work outlined above. It will also be used to assess further experimental visual approach aids.

(h) Ramp/Ski-jump Trial. An adjustable ramp is under construction at Bedford, capable of being set at exit angles of up to 20^{o}. HSA will manage a programme of Harrier launches off the ramp (initially at up to 12^{o}) later this year to assess the performance and handling implications of this aid to launch performance. HSA are at present studying ramp launches on a simulator.

(j) Assessment of Harrier Launch Performance. This topic is part of the Bedford work programme and the rest of this paper outlines the results of some recent studies. It is a co-incidence that John Williams' paper for the V/STOL Workshop is on a closely related topic. The two papers should not be taken as an indication that the UK is studying the STO launch to the exclusion of other aspects of V/STOL operations.

2 THE STO LAUNCH WITH MOTION

It should be relatively easy to avoid bow-down catapult launches because of the short time involved, but this does not apply to maximum performance STO launches. The basic difficulty with an STO launch is that it takes considerably longer than a catapult launch and occupies approximately one cycle of ship pitching motion. In this case the irregularities of ship motion make it much less improbable that the ship will be bows down when the aircraft reaches the deck end.

The current RAF release for Harrier operations from ships requires an additional speed margin of 20 kn to be added for launches in $\pm 1^{\circ}$ of ship pitch motion. This additional speed margin is based on pessimistic assumptions so it should be relatively safe, but it does represent a very large payload penalty. This provides a powerful incentive to refine our assessment in order to ensure that we do not pay an undue penalty for ship motion.

The Sea Harrier is to be operated in conditions of up to $\pm 2^{\circ}$ of ship pitch. The present work represents an attempt to establish suitable criteria to permit such an operation to be conducted safely but without undue payload penalty.

The recent Hermes trial aimed, among other things, to provide additional data on Harrier launch performance to expand the data base for validating our current launch model. The ideal condition for precise validation would, at this stage, be a ship with no angular motion. Unfortunately, conditions during the trial were far from this ideal, but the large motions encountered did provide the opportunity to assess launches under these conditions.

Since the Hermes trial we have had the opportunity to carry our theoretical assessment of STO launch margins with ship motion rather further. The present phase of work is not yet complete but the V/STOL Workshop provides an opportunity to review it and to seek suggestions which might increase its value.

In passing, two additional aspects of operating with ship motion were noted during the Hermes trial. One aspect of launching with a large speed margin which emerged was the fact that a high speed STO launch may well create problems, particularly off a wet deck. These arise because the Harrier's relatively poor directional control at high speed on a wet deck is degraded by the reduction in load on wheels produced by the nozzle angle used for deck run (15° below horizontal) and the effects of ship pitch. In one launch on Hermes the combination of ship motion, a large speed margin to protect against this and a wet deck, combined to produce loss of control over the aircraft's track necessitating premature nozzle rotation and lift-off. Thus, at least in that phase of the ship motion cycle, the large speed margin being applied was not only unnecessary but also created problems. It should be noted that with $\pm 2^{\circ}$ ship pitch, ship motion alone can reduce the wheel reaction by perhaps 30% in part of the cycle. A second aspect to note is that with $\pm 2^{\circ}$ pitch, a point 100 ft from the centre of rotation will have more than $\pm$ 0.1 g acceleration.

3 SHIP MOTION

Ship motion was recorded throughout the flying periods during the Hermes trial. Examples are presented here to illustrate some of the factors which make it difficult to ensure a bows-up STO

launch, or even that any speed margin applied is relevant to the actual amplitude of motion encountered during the launch. The records are of ship pitch angle with the ship steaming into an 18 kn wind at speeds between 10 and 15 kn.

Fig 1a shows the end of a period of 9 minutes during which the pitch had a mean value of about $\pm \frac{1}{2}^{o}$ and was always less than $\pm 1^{o}$. After this long period of relatively small amplitude, the motion suddenly increased to $\pm 1\frac{1}{2}^{o}$ within about one cycle.

Fig 1b was recorded at a different time on the same day. It illustrates a situation where the period of the motion was very irregular. Conditions like this lead to a relatively high risk that the aircraft will reach deck-end when the ship is bows-down.

Fig 2a illustrates beating between the ship's natural frequency and the wave frequency in regular seas. Event marks show the point of initiation of an STO launch and the deck-end point. This launch occurred during one of the largest motion cycles in the period of 5 minutes shown and the end point was only about 1 second from the worst part of the cycle (ie bows-down, going down).

Fig 2b also shows beating, with amplitude varying from less than $\pm \frac{1}{2}^{o}$ to as large as $\pm 2^{o}$. The event marks show an attempt to launch in a lull, which resulted in the aircraft leaving the deck at the worst part of a relatively small cycle.

Observations during the Hermes trial lead to the following conclusions:

(a) It is necessary to look back over several minutes recording taken after the ship has reached the launch conditions, to establish a pitch amplitude which is unlikely to be exceeded during the launch.

(b) It does not appear appropriate to aim to launch during lulls in the motion. The small motion may increase rapidly and there is no indication of the phasing of this change. It was generally agreed in both actual launches and practice dummy launches, that it was much more reliable to wait until a pitching motion was established and then judge the appropriate point in the cycle for launch initiation.

(c) Almost all launches on Hermes were initiated by the Flight Deck Officer. Analysis of the records showed that of 70 launches, 30 occurred in the worst quarter of the motion cycle (although a worthwhile proportion of the 30 were in relatively small motion). This confirmed the general impression that the FDO is not very well placed to judge an STO launch. In the period leading up to the launch his attention must be primarily on the aircraft preparation leaving him little opportunity to judge the current motion

situation; also the deck is not a very good point for observing pitch motion and does not provide the opportunity to see waves coming.

(d) Practice dummy launches from Flying Control suggested that this would be a better observation point for initiating STO launches, provided a procedure was adopted to avoid any delay in signalling to the pilot.

However, even without considering night launches, it seems unlikely that launching in the worst part of the pitch motion cycle can be avoided completely. Thus, at present it appears to be essential to ensure that an STO aircraft will be safe if it leaves the bow at the worst part of the cycle.

This final requirement is the basis of the present RAF margin for the Harrier of + 20 kn for $\pm$ 1° pitch. Based on model calculations for launch at the worst part of the cycle, a margin of 14 kn/ $\pm$ 1° is needed (approx linear to $\pm$ 2°). The additional margin represents a factor to allow for uncertainties in the situation.

4 PRELIMINARY LAUNCH CALCULATIONS

Fig 3 shows the relation between aircraft speed at deck-end and minimum clearance above the sea in the subsequent flightpath, derived from the present Harrier launch model. Four different launch situations are illustrated with aircraft weight, thrust, wind over deck etc, constant in all cases.

(a) Flat deck static. Current RAF operations are based on aiming to launch at the speed indicated. Because of the non-linear relation, speed margin is more significant than height margin. Thus, in this particular case, the target launch speed represents 24 kn speed margin above sea-strike, all also remaining unchanged.

(b) Flat deck pitching. With $\pm$ 2° ship pitch, associated heave, launch in the worst part of the cycle, and all else as in (a); this shows the relation between end speed and minimum clearance above the associated waves. It would be necessary to add 25 kn to the static deck end speed to retain the same speed margin above sea-strike in this case.

Fig 3 presents two more curves to put the picture in perspective.

(c) & (d) Conventional Aircraft. These curves were calculated for a Harrier with its nozzles aft, taken as representing a conventional aircraft being catapulted. In all other respects the data were as for (a) and (b) respectively. Comparison between (c) and (d) shows that the ship motion allowance in this case would be 22 kn to maintain a given speed margin above sea-strike. Thus, a conventional launch appears similar to an STO launch in this respect, but of

course, a catapult launch only takes a short time and therefore should not require protection against the worst part of the motion cycle.

The target launch speed margin is not only a protection against uncertainties in end speed and wind over deck, it must also provide protection against uncertainties in airborne thrust, pilot handling, nozzle angle, etc. Thus, it is only appropriate to retain the same speed margin for a pitching deck as for a static deck if the sensitivity of sea clearance to the various launch uncertainties is similar in the two situations.

The remainder of this paper addresses this question, but first it is necessary to establish a standard basis for comparison. Three representative cases have been chosen, with target end speeds as indicated in Fig 4.

Case 1. Represents a basic case in which the Harrier is loaded to the maximum weight at which it is capable of operating with normal speed margin above sea-strike, from a non-pitching ship at maximum achievable wind over deck.

Case 2. This is a worst-part-of-the-cycle launch with the ship pitching $\pm 2^{\circ}$. Aircraft weight is reduced but all else (deck-run, wind over deck, etc) is unchanged, to give the same sea-strike speed margin as in Case 1. The weight penalty for motion is thus smaller than in the current RAF release, but is still substantial. Note that target end speed has increased slightly because weight has been reduced while deck run and thrust are unchanged.

Case 3. This is a worst-part-of-the-cycle launch with $\pm 2^{\circ}$ pitch as in Case 2, but with the ship fitted with a deck ramp at the bow. The ramp has been sized to permit the aircraft to operate at the original Case 1 weight with deck-run, wind over deck, sea-strike speed margin etc, unchanged. In the present case, this requires a 5° ramp, assumed to be a circular arc 5 ft high.

The next section outlines an assessment of whether it is, in fact, appropriate to use the same speed margin above sea-strike in all three cases.

5 EFFECT OF OFF-DESIGN LAUNCHES

In establishing whether a given target launch speed is adequate it is important to avoid penalising the aircraft unnecessarily by attempting to satisfy the situation where all parameters are simultaneously at their worst possible values. We believe that the present target speed margin above sea-strike used for Harrier launches from non-pitching ships represents a reasonable balance between payload and safety. Therefore, when assessing non-standard launch

conditions they have first been applied to the non-pitching flat deck situation to establish that they are not unrealistically severe.

Significant differences exist between the three basic launch situations outlined above. These differences are best illustrated by comparing the three cases, in the situation where the aircraft leaves the bow at sea-strike end speed, all else being unchanged. Fig 5 shows various significant parameters:-

C_o sea clearance at deck end (ft)

h_o height rate at deck end (ft/sec)

θ_o pitch attitude at deck end (deg)

V airspeed from deck end to min sea clearance point (kn)

$\ddot{x}_f$ acceleration along flightpath at min sea clearance point (g)

T time from deck end to min sea clearance point (sec)

x_f distance from deck end of min sea clearance point (ft)

where the end speed has been selected to give zero sea clearance at the lowest point in the trajectory. The pattern between the three launch cases varies from parameter to parameter. For example:-

Flat deck static. Starts at greatest sea clearance, least rate of descent, least incidence, and takes most time.

Flat deck pitching. Starts at least sea clearance, greatest rate of descent, mid incidence and takes least time.

Ramp pitching. Starts at mid sea clearance, near least rate of descent, greatest incidence and takes mid time.

This suggests that the different cases may well have significantly different sensitivities to different sets of non-standard conditions.

Our model has been used to compare the effects of a limited number of non-standard conditions in the three launch cases, based on target launch speeds as in Fig 4 which give equal speed margins above sea strike. The aim is to establish whether equal margins do in fact provide similar protection in all three cases. For completeness, some data for the Harrier with nozzles aft have been included, to permit a limited comparison with the launch of a conventional type of aircraft.

Fig 6 illustrates the results for an on-design launch and for 7 non-standard sets of conditions. The parameters shown are:-

C_f sea clearance at lowest point in trajectory (ft)

$V_e - V_{ss}$ (end speed) - (sea-strike end speed) (kn)

V_f airspeed at min sea clearance point (kn)

$\ddot{x}_f$ acceleration along flightpath at min sea clearance point (g)

T time from deck end of min sea clearance point (sec)

Launch conditions are made up from combinations of α (angle of attack) and Th (thrust). Four different α histories were used:

(1) $\longrightarrow 12^\circ$ 3°/sec to 12° (standard condition)

(2) $\longrightarrow 14^\circ$ 3°/sec to 14°

(3) S $\longrightarrow 11^\circ$ 1 sec delay then 2°/sec to 11°

(4) S $\longrightarrow 14^\circ$ 1 sec delay then 2°/sec to 14°

Three different thrust situations were used; associated with these there were some other changes as well:

(1) H JPT limiter 5 sec after deck end (standard conditions).

(2) M JPT limiter 3 sec after deck end.
increased bleed.
small increases in weight and ambient temp.
small decreases in WOD, deck run and ambient pressure.

(3) L as M but full bleed.

The three STO launch cases set out in section 4 are presented for each launch condition. For three conditions nozzles-aft launches are included (with and without ship motion); however all these nozzles-aft launches assume the standard bleed associated with thrust situation H.

Fig 6 is presented to illustrate the general picture and is not intended to convey the complete story. Certain conclusions may be drawn from this limited sample of data.

(1) Compare the first and third conditions in Fig 6. The reduced thrust, etc associated with thrust M does not change the balance between STO and conventional launches in terms of minimum sea clearance. However, in terms of end speed margin above sea-strike, it effects the STO launches relatively more severely.

(2) Compare the third and fourth sets of conditions in the figure. Again in terms of end speed margin above sea-strike, the STO launches provide less opportunity for the pilot to use higher incidence to restore the performance lost by being in the thrust M situation than do the conventional launches.

(3) Compare all the sets of conditions in the figure. In terms of end speed margin above sea-strike, STOs from a pitching ship ('STO Pitching' and 'STO Pitching With Ramp') appear to be rather less sensitive to non-standard conditions than do STOs from a static (flat) ship.

(4) In only two of the ramp launch conditions assessed does the flightpath have any period of sink. The ramp launch retains a continuous climb in conditions where the end speed margin is relatively small, eg in the fifth set of conditions in the figure.

6 FURTHER WORK

It is important to remember that the present calculations are only as good as our existing launch model. This model is difficult to validate because for most real life launches the predicted and actual sink after launch are small, making it difficult to confirm sink curves such as shown in Fig 4. There have been some Harrier launches with substantial sink,but normally under conditions where large sink had not been expected, eg launch 39 on USS Roosevelt. Unfortunately, data has not been available on all the relevant parameters so it has proved difficult to test the validity of the model.

Several launches during the Hermes trial produced significant sink. The data for these is being extracted prior to a model matching exercise which may give some further indication of the model's validity.

The coming ramp trial at Bedford should also be valuable in providing data. It will be possible to conduct this under more controlled conditions than normally apply at sea and detailed kine-theodolite measurements of the flightpath will be available for the first time.

There is, however, a fundamental difficulty when attempting to establish the validity of the model. Considering energy, at the relevant flight conditions the kinetic energy associated with 1 kn speed change is equivalent to the potential energy associated with 10 ft height change. Considering work, the work done along the flightpath to its lowest point is perhaps ten million ft lb compared with about twenty thousand ft lb for 10 ft height change. These equivalencies illustrate the fact that height change is a relatively small term in the situation and suggest that height matching will always be uncertain.

However, these uncertainties should not prevent the model from indicating trends and general sensitivities to a reasonable level of accuracy, so the results in the present paper are believed to be valid.

7 DISCUSSION AND CONCLUSIONS

Based on the limited sample modelled, launches with ship motion from a flat deck or ramp appear to have about the same sensitivity to non-standard launch conditions as have alunches from a flat non-

pitching ship. Hence with ship motion it may be appropriate to use the same speed margin above sea-strike as is currently applied for a flat non-pitching ship. The present calculations also suggest that a motion allowance of about 13 kn/$\pm$ 1° of ship pitch is required.

However, the speed allowance for ship motion must also recognise the risk that the motion at the instant of leaving the deck may be larger than assumed when setting up the launch. The present brief study suggests that this additional uncertainty is the factor most requiring further study.

The magnitude of the allowance required for ship motion depends on the method of assessing amplitude. Taking the mean amplitude of the last 10 cycles would require a large speed allowance per degree; taking the largest amplitude in the last 100 cycles would require a smaller allowance per degree. Although in the latter case the actual allowance in knots might be larger or smaller depending on the regularity of motion on that occasion, it would overall represent a smaller mean payload penalty for a given level of safety (or a higher safety level for a given mean payload penalty, depending on the relative magnitude of the motion allowances applied). Unfortunately, it would create operational problems if in marginal conditions a ship had to steam for perhaps 10 minutes under launch wind over deck conditions in order to establish whether the motion was outside limits for that wind over deck level.

Any method of predicting ship motion for 10 seconds ahead with reasonable accuracy would permit a substantial gain in safety, payload and operational flexibility. The prime requirement is to be able to predict the phase of the motion to within $\pm$ 45° to some high level of confidence.

The data presented here also illustrate an aspect of the ramp launch which may be significant. When the speed margin above sea-strike is only a few knots, the aircraft can still have a continuously climbing flightpath. Hence, in a marginal ramp launch situation there may be little to alert the pilot to the need for corrective action, until a late stage when it will be more difficult to retrieve the situation.

Further work is required to check the validity of the launch model used at present.

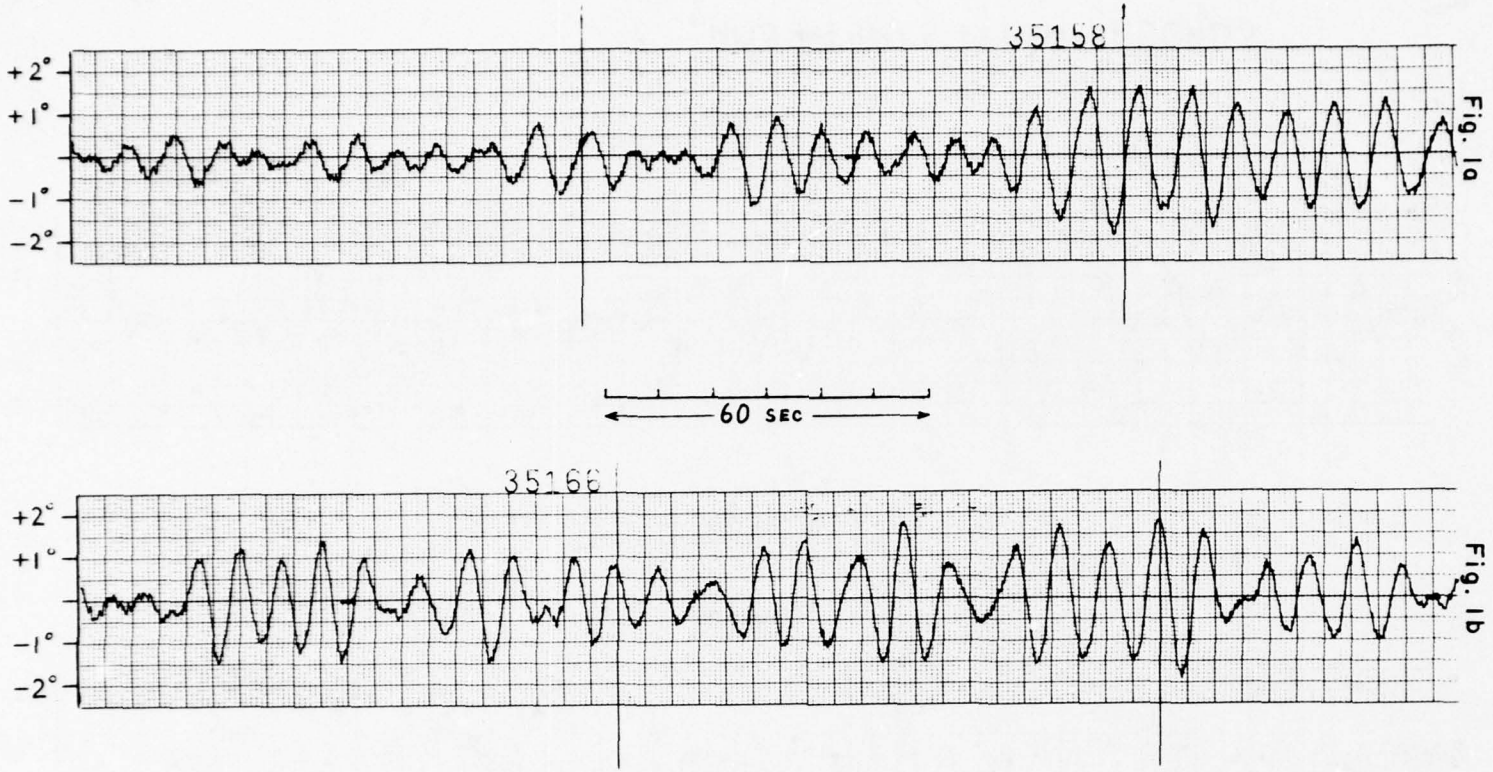


Fig. 1a

Fig. 1b

FIG. 1

HMS HERMES PITCH RECORDS

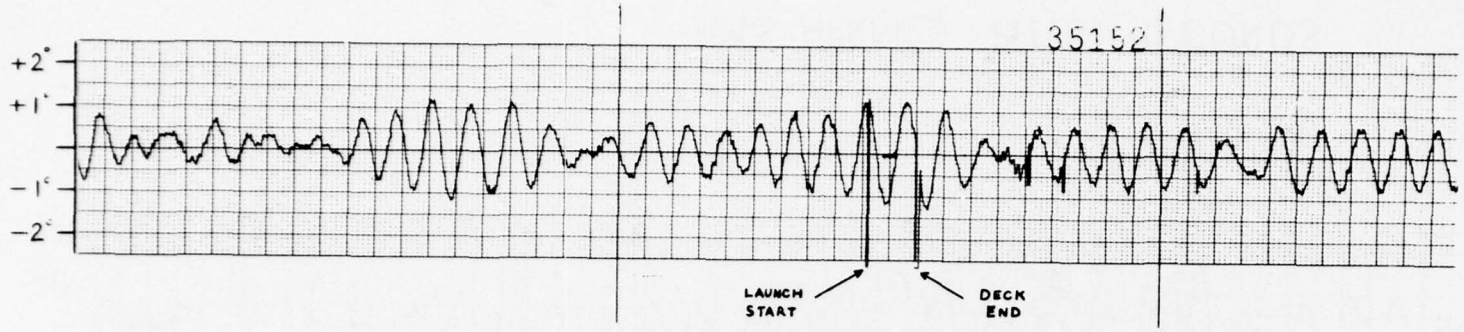


Fig. 2a

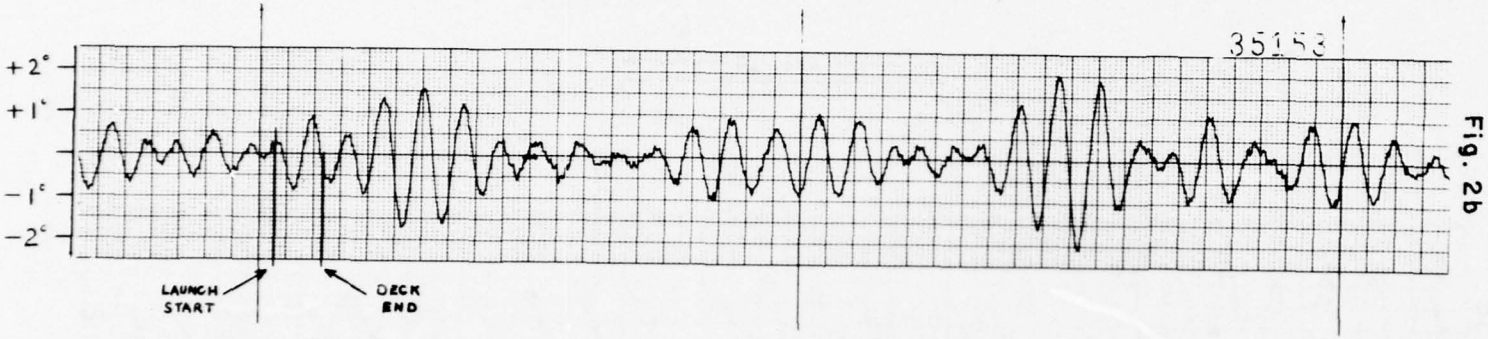


Fig. 2b

HMS HERMES PITCH RECORDS

FIG. 2

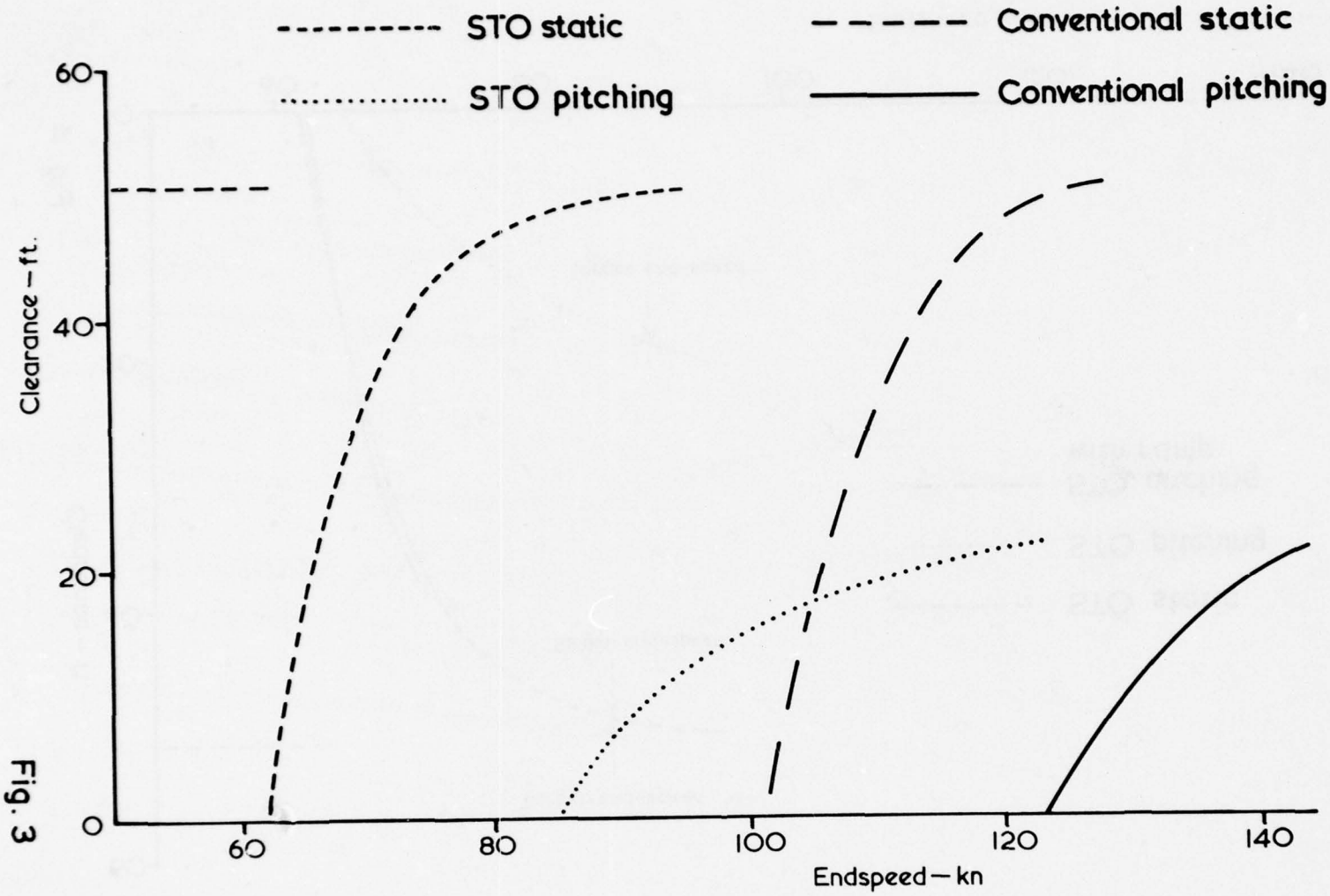

STO static
STO pitching
Conventional static
Conventional pitching
Clearance – ft.
60
40
20
0
60
80
100
120
140
Endspeed – kn

Fig. 3

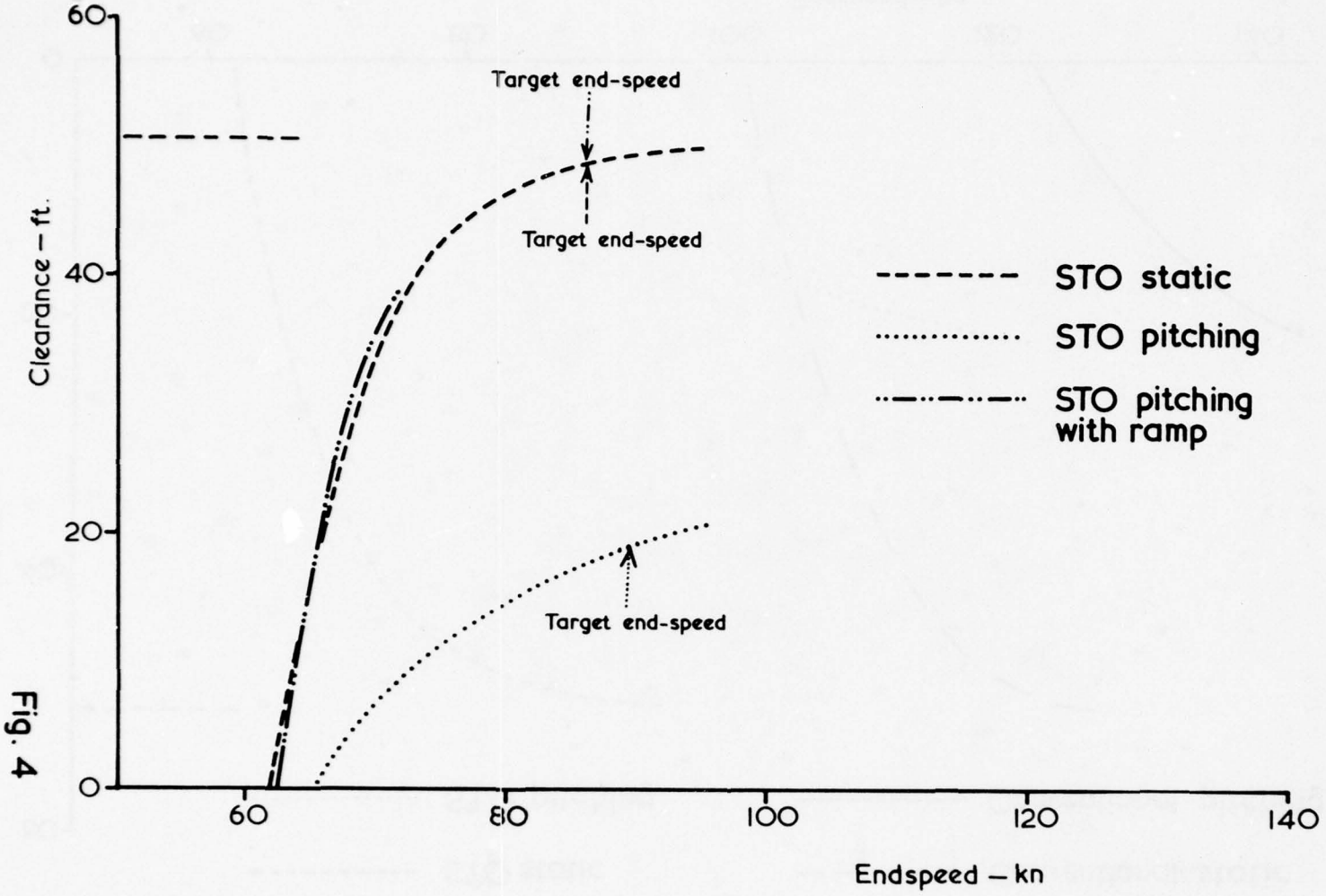

60
40
20
0
Clearance – ft.
Target end-speed
Target end-speed
Target end-speed
STO static
STO pitching
STO pitching with ramp
60
80
100
120
140
Endspeed – kn

Fig. 4

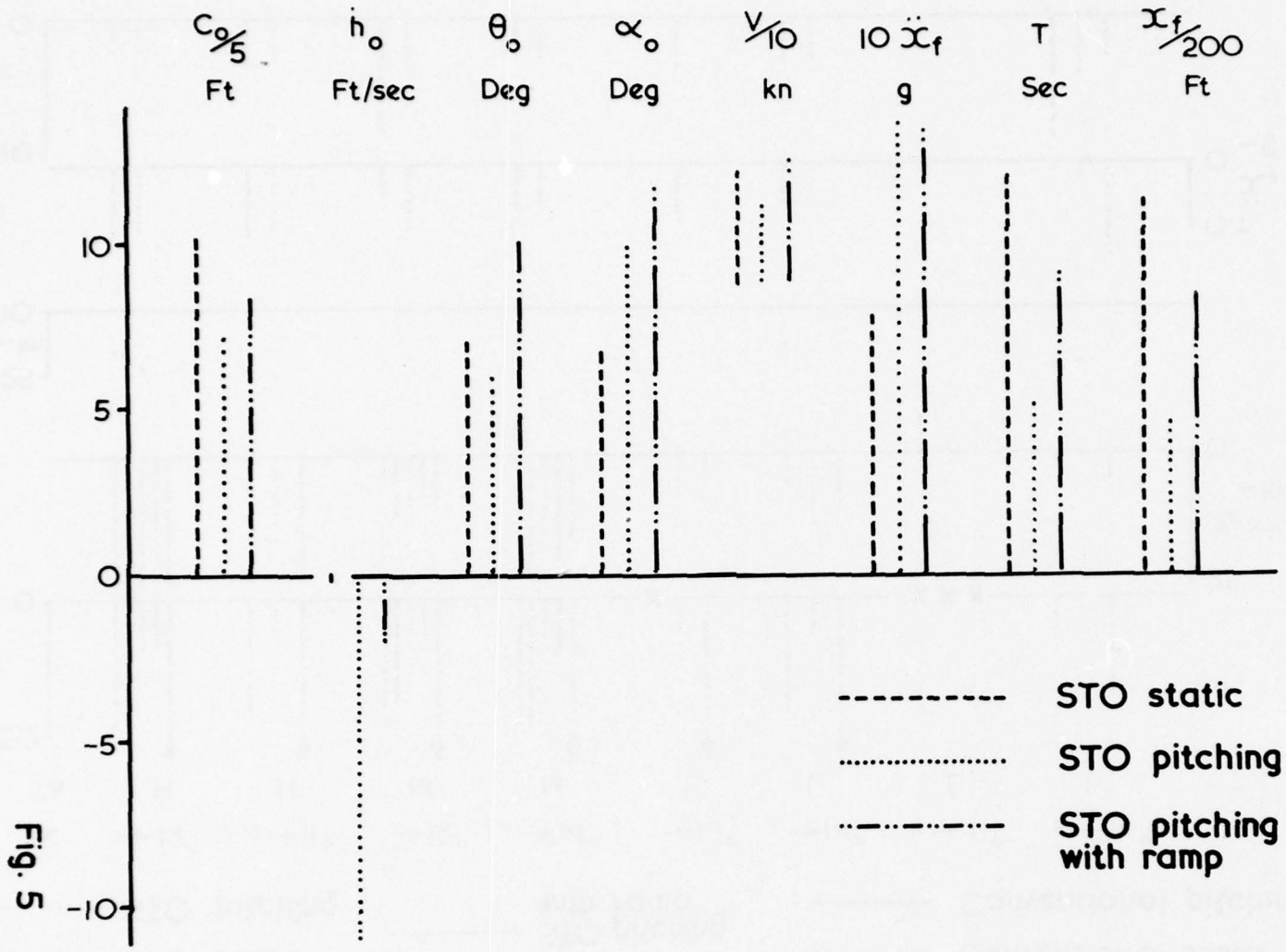

$C_o/5$
Ft
$\dot{h}_o$
Ft/sec
θ_o
Deg
α_o
Deg
$V/10$
kn
$10\ \ddot{x}_f$
g
T
Sec
$x_f/200$
Ft
10
5
0
-5
-10
STO static
STO pitching
STO pitching with ramp

Fig. 5

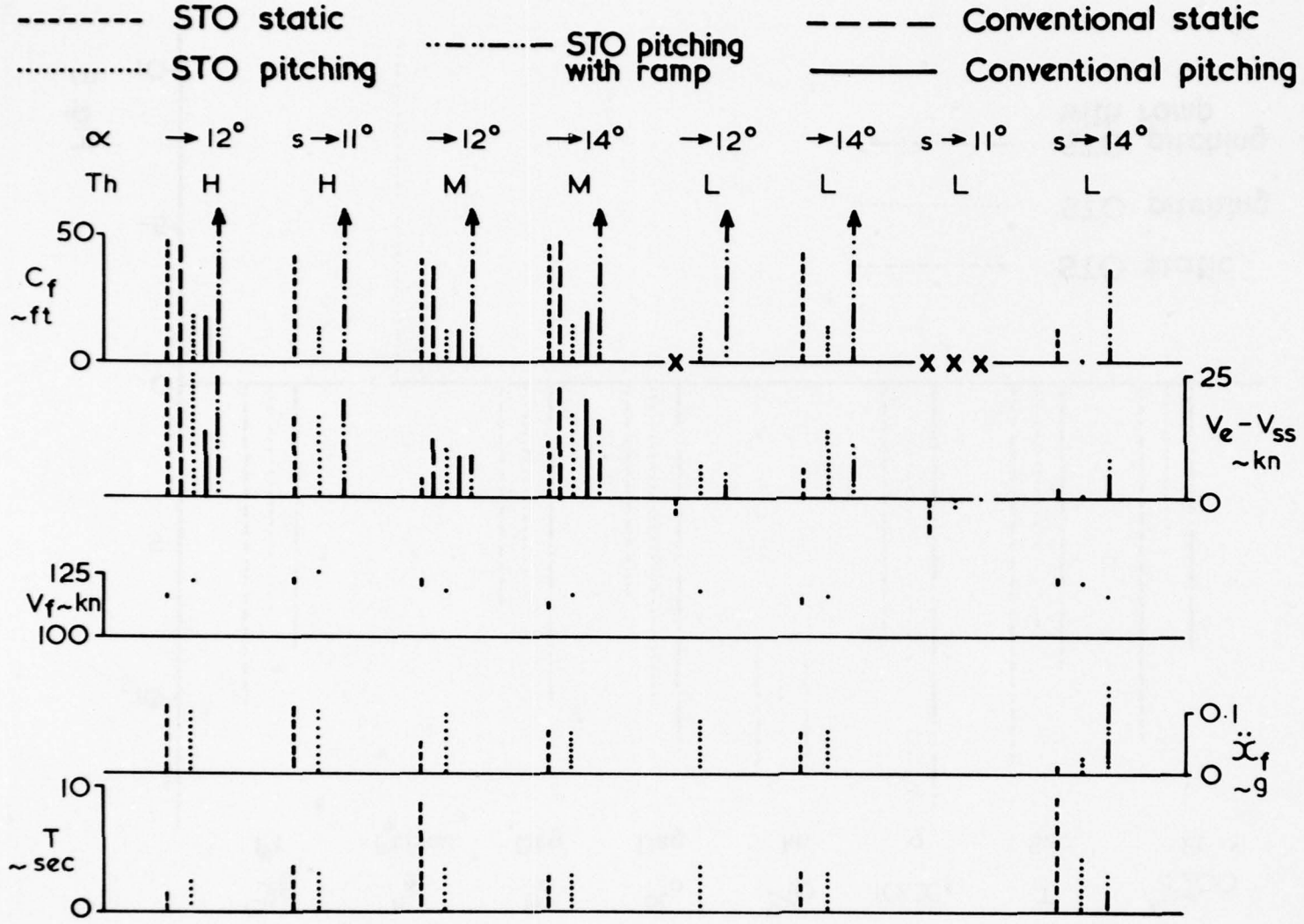

STO static
STO pitching
STO pitching with ramp
Conventional static
Conventional pitching
∝ →12° s→11° →12° →14° →12° →14° s→11° s→14°
Th H H M M L L L L
50
C_f ~ft
0
25
$V_e - V_{ss}$ ~kn
0
125
V_f ~kn
100
0·1
$\ddot{x}_f$ ~g
0
10
T ~sec
0

Fig. 6

Ronald Hess: It would seem that by understanding the art of signal application, you could do a very good job of estimating when the ship nose were coming up and when it were going down at a fraction of the cost of building a ramp. You wouldn't have to know exactly what the precise nose-up attitude was going to be, but just that the ship motion model would provide a 99 percent probability of having the proper aircraft departure condition.

Nichols: We haven't had a chance to consider yet whether ship motion modelling could be of help. And I believe the question of looking at the waves as they approach the ship may provide some assistance. In any event, I'm hoping that we may hear some more on this subject tomorrow during the ship motion presentation, but I could be wrong.

Andie Byrnes: Under normal conditions, when the deck is flat at take off, what's your criteria for selecting the minimum launch speed in terms of acceleration capability?

Nichols: Well, the present basis has been to design the process so that we station the nozzle angle which in turn permits the aircraft to go off at the lowest possible speed before it reaches a sea strike when given a nominal incidence history. Then we apply a margin above that which is fairly arbitrary. At present in the U.K., we have been using the speed that would give us a fifteen foot sink plus (say) another fifteen knots. In terms of the longitudinal acceleration, we were looking for a situation where, if you were going off at the speed that would correspond to sea strike, then you would have roughly 0.1 of a "g" available or between one and half to two knots a second, perhaps.

Tom Lacey: Does your ship model assume anything as to ship heave, or is it all just pitch?

Nichols: No, the model here is for a ship in a sinusoidal sea. It is heaving as well as pitching with an appropriate phase relation between them. But it is a sinusoidal sea.

Lacey: Thank you.

Anon: Is there anything significantly different when they're talking about a through deck cruiser rather than a flat-type carrier on which your model was based?

Nichols: No. The figures that I have had to date aren't that different, although there is some difference in just what sea state is needed to produce the pitch. Once you've established the pitch, assuming that we talk in terms of pitch rather than the sea state that produces it, the difference seems pretty small.

Anon: Is the height of the deck the only substantially different factor?

Nichols: Yes, I think so. But as I have said, at the moment, the model is used only to show trends. I would prefer to be rather cautious in predicting absolute numbers from it.

SHIPBOARD TESTING OF THE AV-8A "HARRIER"

by

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Naval Air Test Center
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The AV-8A has been involved in U.S. shipboard operations since 1971. Since that time several shipboard test efforts have been conducted aboard LPD, LPH and CV class ships. However, these tests were usually uninstrumented and little data were obtained to provide fleet operating limits. The recent shipboard tests aboard USS F. D. ROOSEVELT were the first to provide any significant recorded data. The AV-8A/FDR tests included: minimum end airspeed flying qualities and performance, optimum STO trim settings, effects of mistrim on STO flying qualities, dynamic interface (STO, VTO & VL), approach and VL flying qualities and effects of inboard tanks in combination with outboard stores.

This paper will discuss results of shipboard testing of the AV-8A in the U.S. with particualr emphasis on the FDR tests because of the limited data available from other shipboard tests. The primary area of discussion will be flying qualities, to provide "lessons learned" information for the benefit of the workshop members. It should be noted that in the case of the AV-8A, it is impossible to totally separate flying qualities from performance due to the design of the reaction control system (RCS). The AV-8A RCS utilizes engine bleed air to provide three axes control in the jetborne and semi-jetborne regions of flight. The three axes limited authority stability augmentation system (SAS) also utilizes this same RCS in these flight regions. Increased pilot or SAS control usage, increases engine bleed, decreases thrust and reduces

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performance. This interaction of flying qualities and performance due to the RCS produces a "cliff edge" effect when nearing either a flying qualities or performance limit, especially when jet pipe temperature (JPT) limited. The current AV-8A RCS engine bleed air method of jetborne and semi-jetborne control, which affects engine thrust, should be avoided in future designs of NAVY VSTOL aircraft.

Prior to shipboard tests, shorebased tests are conducted to obtain tailplane trim data in semi-jetborne flight. These data are obtained by flying constant airspeed, constant nozzle angle, constant power (90-95% NF) spirals (free air trim) at increasing AOA. The data are plotted as shown in figure 1, which shows FDR data with inboard 120 gal tanks, outboard LAU-69 and fuselage gun pods.

The data of figure 1 are utilized to estimate shipboard STO longitudinal trim settings by using the tailplane to trim at 8 units AOA. (The reasons for not using data for 12 units AOA, the optimum fly-away AOA, will be explained later). These data are affected by cg position, aircraft loading, nozzle angle and airspeed. These various affects have been documented by U.K. tests with data presented in a Hawker-Siddeley Aircraft (HSA) report. In general, the results were as follows:

a. Most nose down tailplane required at 120 kt.

b. 50 deg nozzle angle most destabilizing.

c. Inboard 120 gal tanks require approximately 3/4 deg more nose down trim at a given cg position than clean wing.

d. Inboard 300 gal tanks require approximately 4-1/2 deg more nose down trim at a given cg position than clean wing.

e. And of course, more aft cg positions require more nose down tailplane trim.

After allowing for nozzle angle and airspeed affects, the data are presented as shown in figure 2 which compares FDR and GUAM data for the same loading. As 7 1/4 deg of nose down tailplane trim is available, these data indicate the maximum aft cg position limit for a given loading. The difference in the data directs attention to the possible affects of engine center of thrust, since the only documented difference between the two test aircraft was 0.4 in. of more aft center of thrust for the FDR aircraft. (It should be also noted that the FDR data were obtained from telemetered instrumentation, while the GUAM data were obtained from pilot observation of cockpit data.) Only nozzle angle or, more importantly, airspeed changes can reduce the tailplane requirement. In the case of a loading with 300 gal tanks inboard, almost 40 kts (above 120 kts) is required to maintain tailplane trim within the current trim authority. The high airspeed required results in restrictive shipboard WOD for even the largest of dec ks (CV class) and eliminates this loading as a viable fleet shipbaord operational loading. Additionally, 11 1/2 deg of total nose down tailplane authority is available. During shorebased semi-jetborne trim build up to aft cg positions with 300 gal tanks inboard, full forward stick was insufficient to arrest an increasing AOA and pitch attitude at only 11.1% MAC (empty tanks/partial internal fuel) as shown in figure 3. The pilot had to reduce nozzle angle to regain control.

As previously mentioned, the shorebased free air trim data are used as an estimate of shipboard STO trim settings. It should be stressed that this is only an estimate, or more appropriately, a starting point from which to deviate. The optimum shipbaord STO trim setting is a trade-off between the trim required to minimize the nose down pitch

rate generated during nozzle rotation ("the nod") and the trim required for a 12 unit AOA post launch fly-away. Insert discussion on the nod, if appropriate. A shipboard STO trim setting (or pilot input) which reduces the nod to near zero could be insufficient to control AOA to the desired 12 units with the current SAS (Figure 4). As a result, full forward stick was momentarily utilized in this example to control AOA/ pitch attitude. A trim setting determined from free air trim data at 12 units AOA would allow a severe nod with either, a pilot aft stick input to counter the nod with an attendant pitch up, over-rotation and full forward stick secondary correction or excessive sink off the bow and slow rotation to 12 units AOA, with attendant performance loss due to inefficient use of wing lift. Figure 5 shows a near optimum trim setting for the minimum end airspeed launch of the FDR tests. It is only "near" optimum because the time to obtain the optimum 12 units AOA is over 2 sec after leaving the bow. Other shipboard tests, including the recent U.K. tests aboard HMS HERMES, have shown that controllable pitch rates can be achieved with 12 units AOA obtained in approximately 2 sec which provides efficient utilization of wing lift.

The pilot technique, or more correctly, the perceived pilot task influences the optimum trim setting and the post launch flying qualities. Three pilot tasks during shipboard STO are considered below:

(1) rotate to and maintain 12 units AOA.

(2) "hands off" except to check forward to maintain 12 units AOA.

(3) maintain a constant pitch attitude.

Pilots task (1) requires the most pilot workload in that the pilot rotates the airplane to counter the nod reinforces the aerodynamic pitch up following the nod and requires excessive forward stick to correct. Pilot task (2) can be consistently flown by experienced pilots with the correct trim

setting but becomes more difficult when either under-or over trimmed. Pilot task (3) has the potential to be the most repeatible, least demanding task but the current AV-8A pitch attitude display with major divisions every 30 deg is inadequate for this task. Therefore, pilot task (2) is the current USMC recommended shipboard STO technique. It should be mentioned that the U.K. Sea Harrier will have a 1 to 1 pitch display to provide the pitch attitude display accuracy necessary for pilot task (3). Unfortunately, insufficient data are available, at this time, with the improved pitch attitude display during shipboard STO operations.

The VTO is not utilized very extensively during current shipboard operations because of the limited payload available compared to a STO. However, to provide aircraft weapon systems on smaller ships in the furture, the VTO may be the only possibility. The AV-8A shipboard VTO flying qualities are relatively well behaved and controllable under conditions of low wind over deck (WOD), minimum deck motion and adequate performance margin. Figures 6 and 7 provide a comparison of lateral control requirement differences as a result of performance margin. In figure 6, a short lift dry "good go" VTO, the lateral control requirements were a miximum of 6 deg. In figure 7, a short lift wet "slow go" VTO under similar ambient and wind conditions, the maximum lateral control requirements were near full deflection in both directions. This phenomena obviously occurs because of the increased time in ground affect during the "slow go" VTO. With a limited authority SAS, many VSTOL design will exhibit this tendency.

The effects of deck motion, turbulence, and WOD and VTO and VL are not well documented with test data. However, some obvious effects on both VTO and VL can be discussed. With increasing deck motion, the

pilot workload increases due to differential deflection of the exhaust plumes from the deck to the underside of the wing (figure 8). This effect is further aggravated in the VL case by the pilot tendency to "chase the deck" in close. Turbulence in the take-off/landing area produces increased pilot inputs to maintain wings level. The effects of WOD on VTO and VL flying qualities are primarily limited to controllability in crosswind. Whenever the aircraft wings are not parallel to the deck and at less than 20 ft. altitude, the high velocity exhaust gases differntially deflect the deck to the underside of the wing causing rolling moments which aggravate the situation. (Figure 8) Deck motion, turbulence or WOD could individually or in combination cause the aircraft wings to deviate from parallel to the deck. In the case of a VL to a moving deck, the pilot tendency to "chase the deck" in close can only cause the landing to deteriorate. The effects of high WOD on VL lateral control requirements can be seen in figure 9. In this case maximum lateral control requirements of 6 deg left and 9 deg right were required. It was found that a significant reduction in lateral control requirements under similar wind conditions could be achieved by maintaining a slight forward speed (5-10 kt) resulting in a roll-on VL. Figure 10 shows the reduced lateral requirements, only $\pm$5 deg, prior to touchdown when the ROVL technique was used.

The AV-8A approach phase is limited by pilot workload, especially at night or in aft cg position/external store loadings. The current AV-8A shipboard approach profile was designed to reduce the pilot workload in the relatively unstable flight regimes associated with the decelerating transition to the hover. The recommended shipboard approach profile is stepped, to isolate the requirements to decelerate from the requirements

to descend. The AV-8A handling qualities are significantly degraded to nozzle angles greater than 30 deg. Therefore, the change from 20 deg to 40 deg of nozzle angle is not recommended until 3 mi in level flight and if good line-up exists. As can be seen in figure 11, except for the visual deceleration/descent from the hover stop at 1 mi., the level flight portions are used for decelerations and nozzle angle changes. During decents the nozzle angle and airspeed are kept constant to reduce pilot workload requirements.

Although the current approach profile is designed to reduce pilot workload, significant pilot workload still exists especially at night is aft cg position loadings. Figure 12 present data for a night carrier -controlled approach (CCA) during which the ship changed heading with the aircraft within 3 mi. at 40 deg nozzle angle. It can be seen that as the pilot inputs lateral stick to correct to the new ship heading, the AOA increases to 16 units before the pilot reacts with increased power. The increasing AOA with no change in tailplane position indicates a sink rate which if undetected due to other pilot workload factors (heading change) could be disastrous.

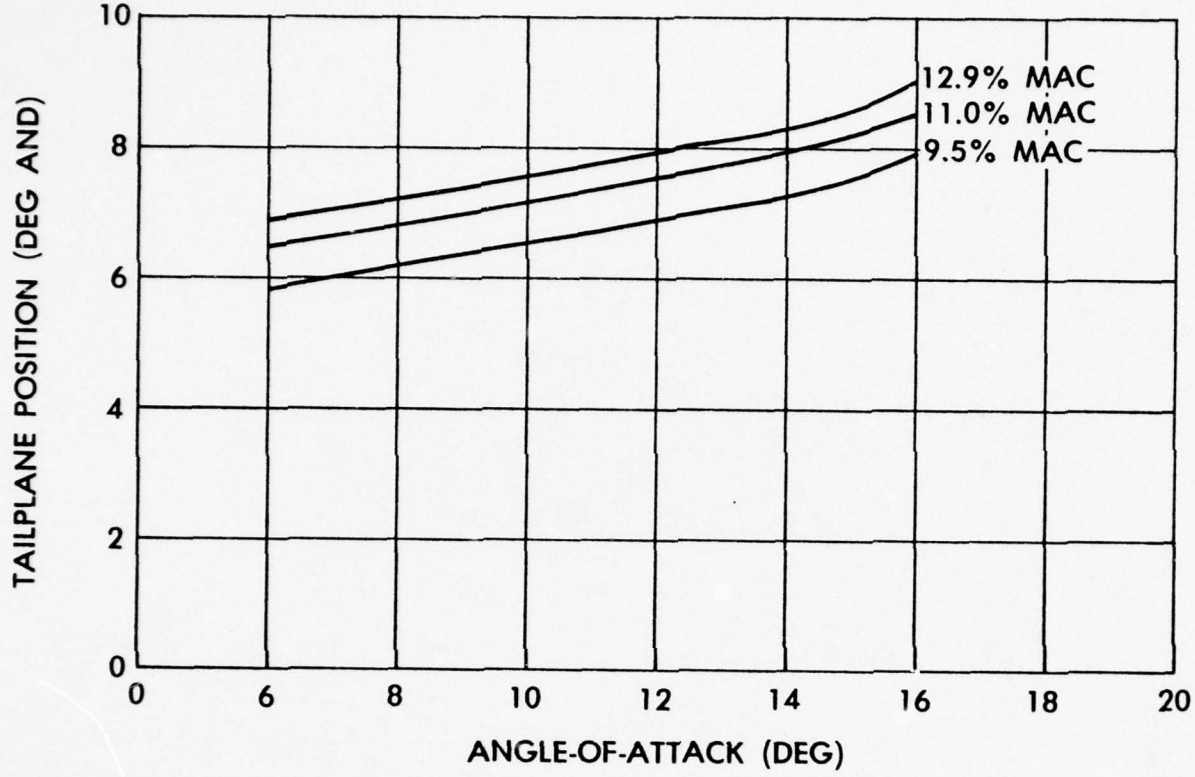
The objective of this workshop is to provide technical guidance for future NAVY and NASA VSTOL aircraft designs. Therefore, several recommendations can be made based on the experience of the AV-8A in the shipboard environment. (Figure 13). The flight control system and limited authority SAS of the AV-8A is insufficient in some of the shipboard operational circumstances encountered. Future VSTOL aircraft should provide a combination flight control/stability augmentation system which will ensure capability of all operational tasks with headwind up to 45 kt and crosswind component up to 30 kt with 20-30% control margin

above stabilization and task levels about all axes. Graphically, figure 14 details the concept of a control margin above stabilization and task levels. Basically, the total control authority of an aircraft design is made up of pilot inputs (workload) and SAS inputs. Future VSTOL designs should provide an adequate SAS to reduce pilot workload to an acceptable level for maintaining flight conditions - hover, glide slope, climb out - under some level of turbulence, deck motion, mistrim, etc. In addition, 20-30% control authority should be available to the pilot to maneuver the airplane in emergencies. Also, the design should ensure carrier controlled approach (OCA) to 200 ft and 1/2 mi, in the 60-90 kt speed range, to achieve a hover within 1/2 mi with a single thrust vector control change - under the most critical recovery loading and under IMC conditions in the semi-jetborne phase (FIGURE 15).

Although this workshop is primarily concerned with aircraft requirements, it would be negligent not to metion that ship design can significantly reduce aircraft requirements. The potential benefits of trade-offs between aircraft and ship design have not been adequately realized. A grated/fluted take-off and landing area could reduce the complexity of the flight control and stability augmentation system required in the aircraft and also improve performance. Ship stabilizatien systems (semi-submerged platform (SSP)) or hull design could reduce deck motions in high sea states and nearly eliminate the adverse effects of deck motion on aircraft flying qualities and pilot workload. New design ship superstructure could reduce turbulence in the take-off and landing area and provide increased operational flexibility. Even the British "ski jump" might provide reductions in pilot workload during STO operations.

In summary, it is believed that a VSTOL aircraft can be designed to land on a ship at sea in near zero, zero weather. A VSTOL aircraft with vectored thrust, attitude and heading stabilization, integrated cockpit display, simplified controls and automation (digital fly-by-wire) should meet this requirement.

AV-8A/368 FREE AIR TRIM



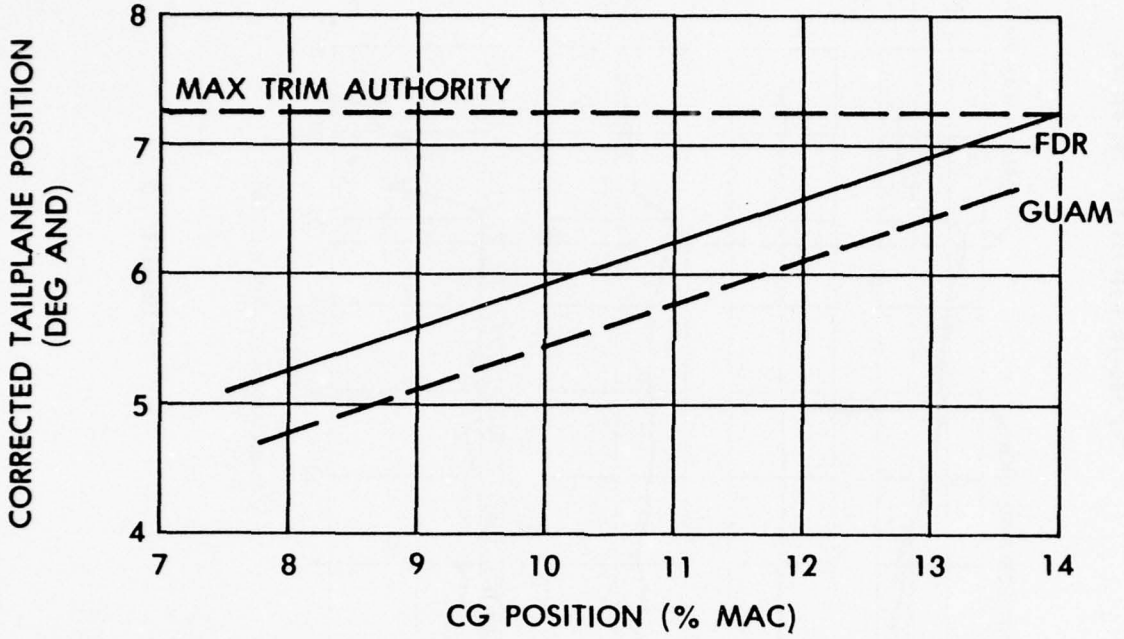
120 KT 65 DEG Θ_j

LOADING: 120 GAL TANKS I/B LAU-69 O/B FUSELAGE GUN PODS

TID-A-3172-Y

FIGURE 1

AV-8A/368 TAILPLANE TO TRIM AT 8 UNITS AOA



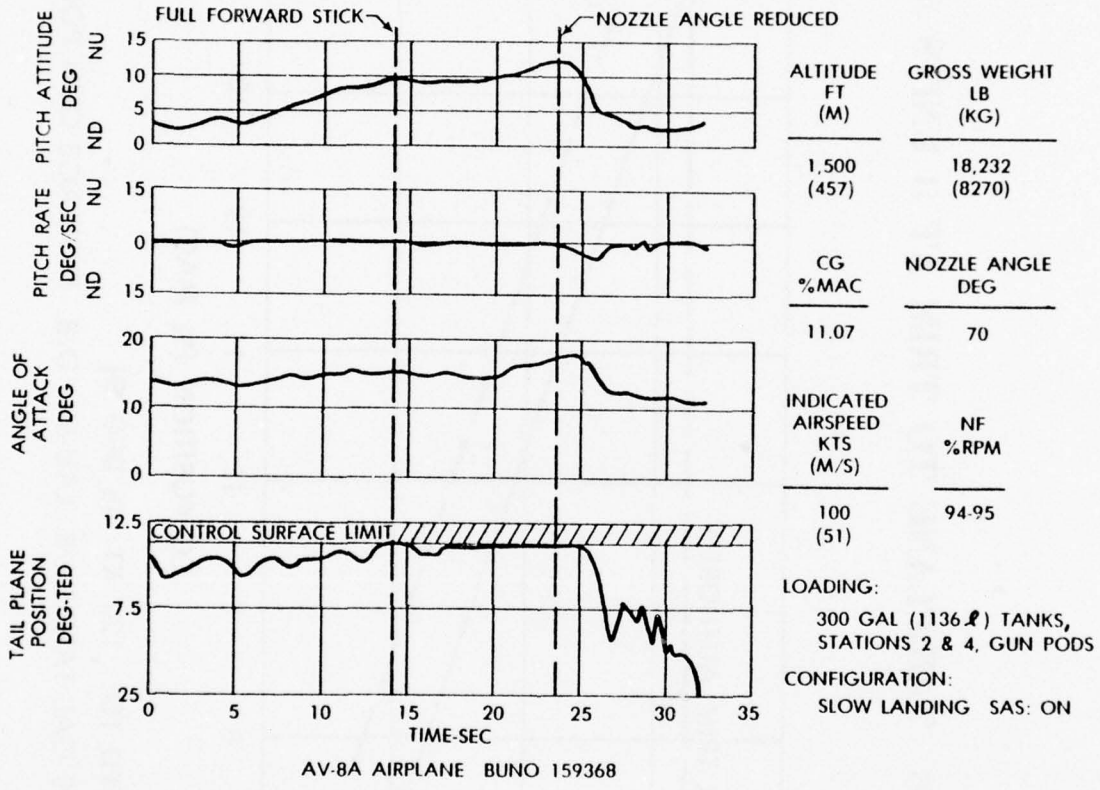
DATA CORRECTED TO: 120 KT 55 DEG Θ_j

LOADING: 120 GAL TANKS I/B LAU-69 O/B FUSELAGE GUN PODS

TID-A-3171-V

FIGURE 2

SEMI-JETBORNE SPIRAL



AV-8A AIRPLANE BUNO 159368

FIGURE 3

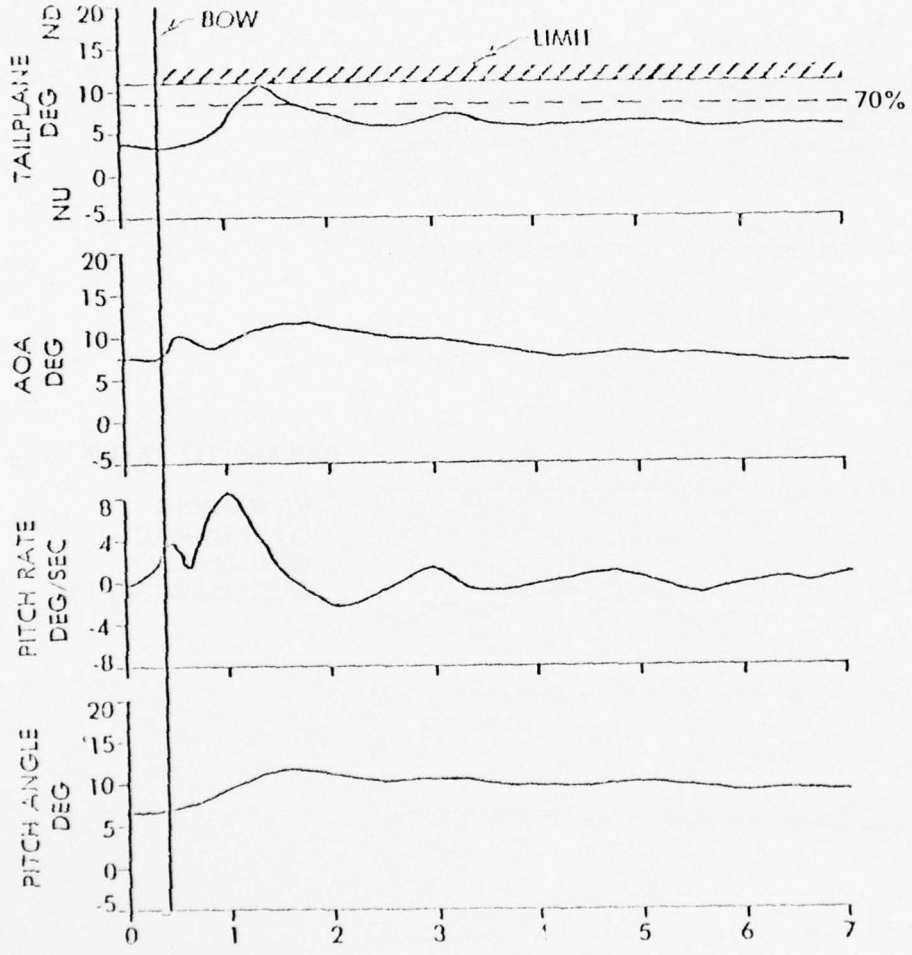

TAILPLANE DEG ND NU
20
15
10
5
0
-5
BOW
LIMIT
70%
AOA DEG
20
15
10
5
0
-5
PITCH RATE DEG/SEC
8
4
0
-4
-8
PITCH ANGLE DEG
20
15
10
5
0
-5
0
1
2
3
5
6
7
DAY STO FLT 44/FDR
VA LOADING
CG 11.8%MAC
WOD 27 KTS
TASK ROTATE
TO 12°

FIGURE 4

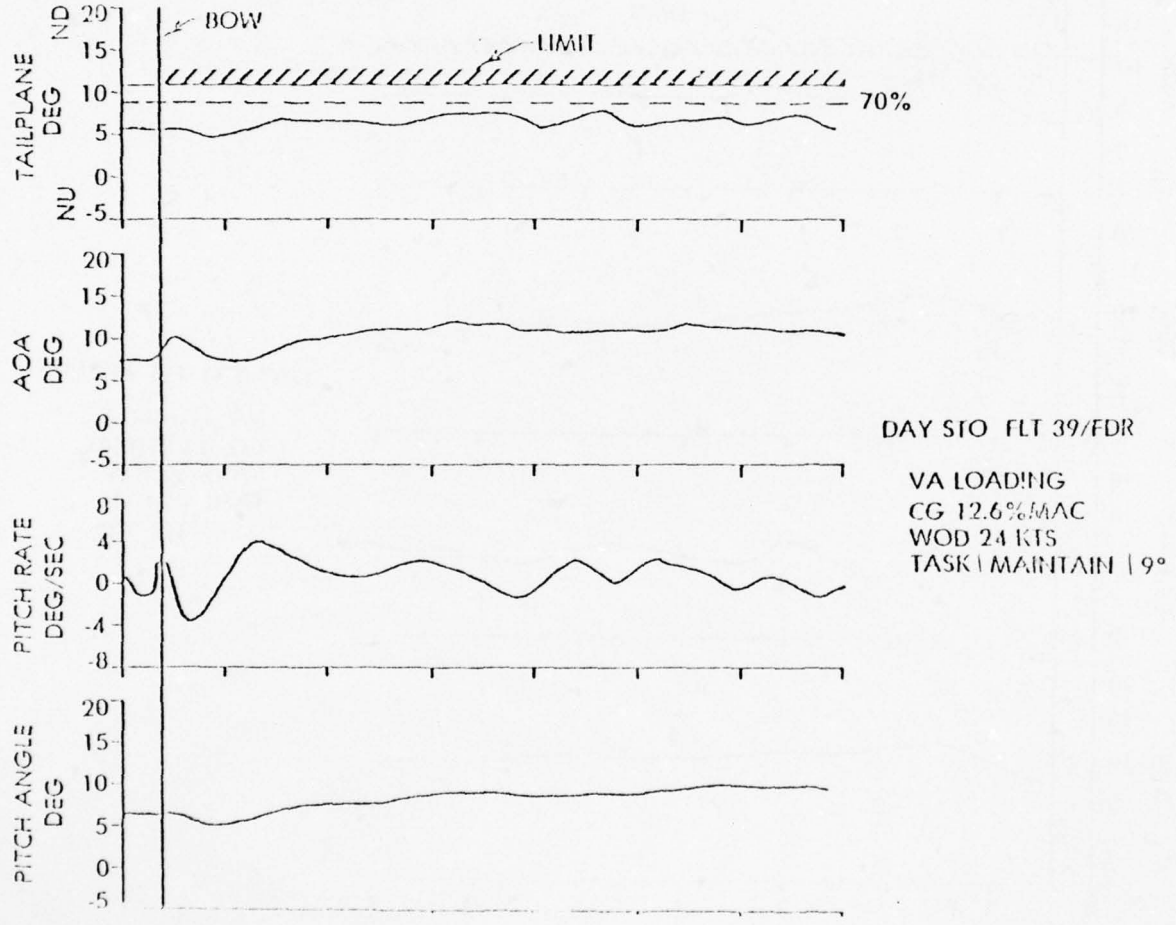
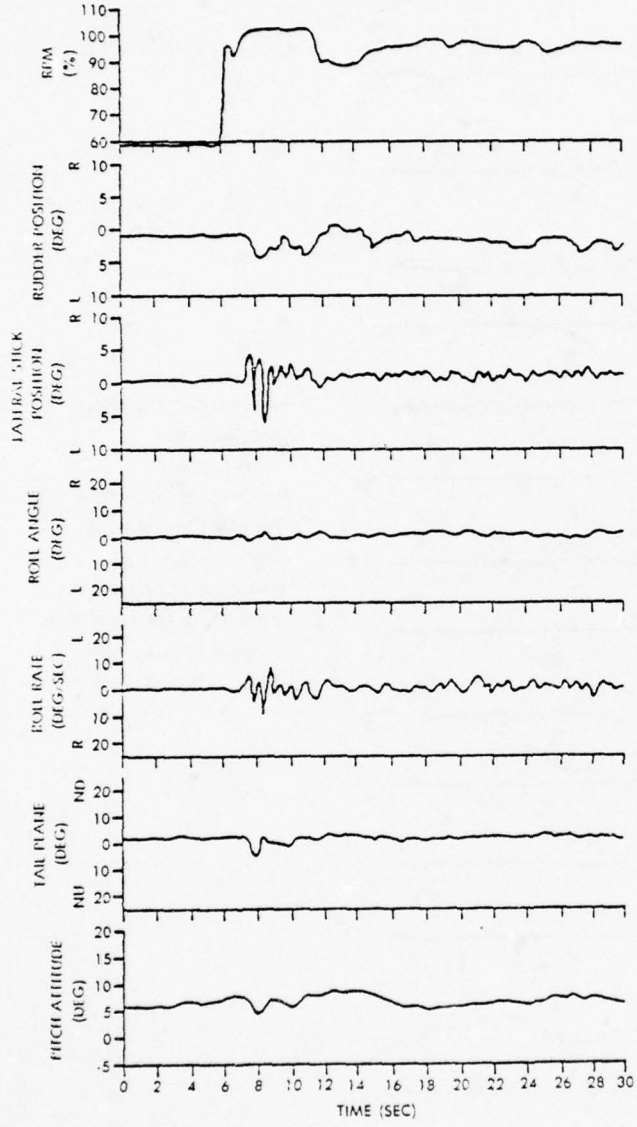
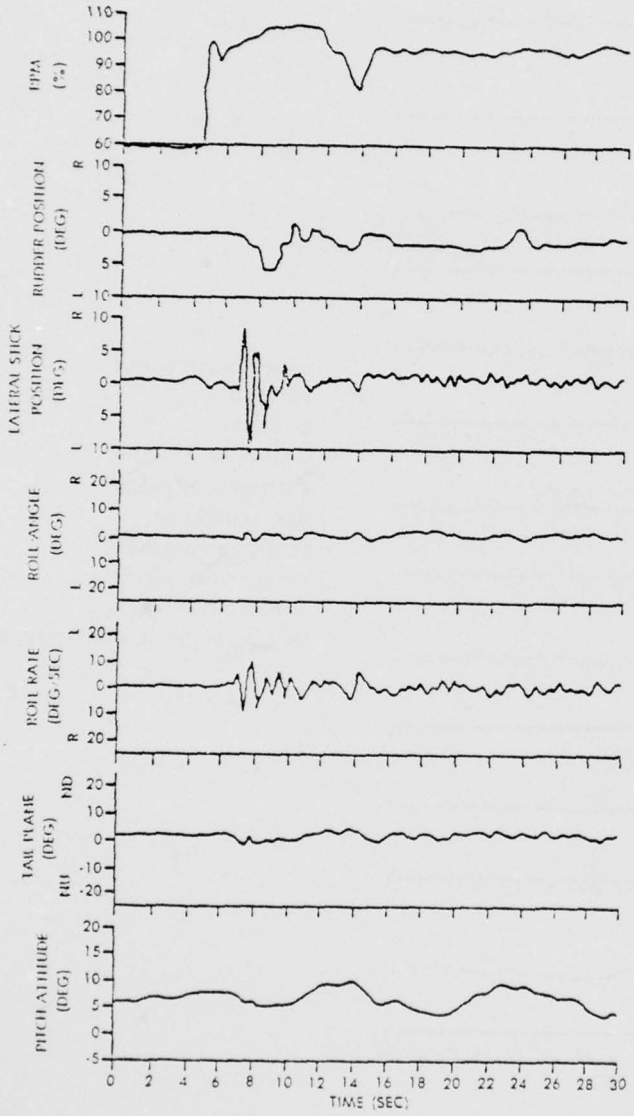

BOW
LIMIT
70%
TAILPLANE DEG
ND
NU
20
15
10
5
0
-5
AOA DEG
PITCH RATE DEG/SEC
8
4
0
-4
-8
PITCH ANGLE DEG
DAY STO FLT 39/FDR
VA LOADING
CG 12.6%MAC
WOD 24 KTS
TASK I MAINTAIN I 9°

FIGURE 5



AV-8A FLIGHT 27 EVENT 3
VTO "GOOD GO"
RATING: SLD
LOADING: PYLONS, CLEAN
GROSS WEIGHT: 14800 LBS
WOD: 17 KTS AT 85°
SHIP MOTION: NEGLIGIBLE
AMBIENT TEMPERATIRE:77° F
AMBIENT PRESSURE: 30" Hg
SHORE BASED VTO CAPABILITY: 15500 LB

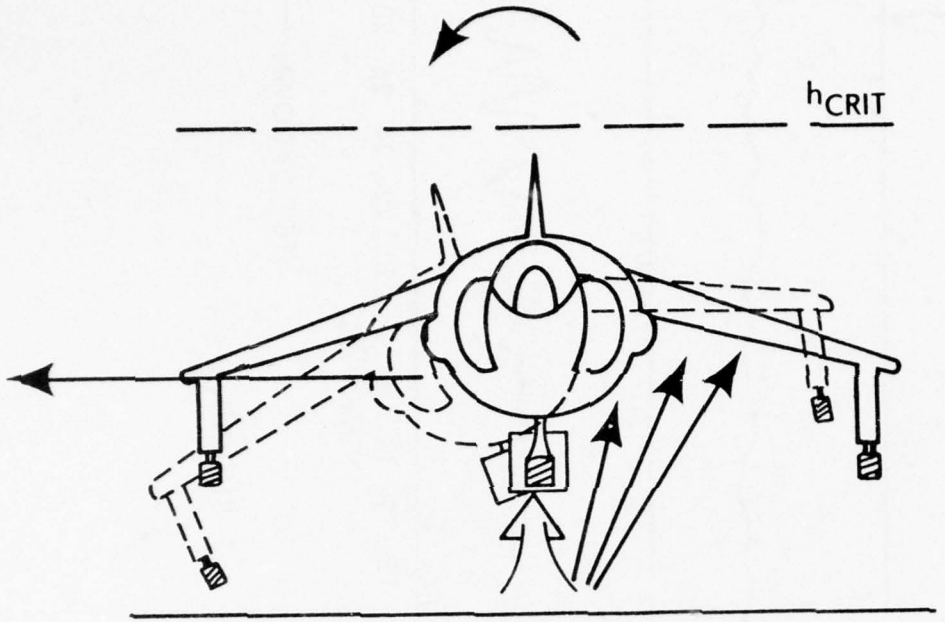
FIGURE 6



AV-8A FLIGHT 27 EVENT 2
VTO "SLOW GO"
RATING: SLW
LOADING: PYLONS CLEAN
GROSS WEIGHT: 15400 LBS
WOD: 15 KTS AT 90°
SHIP MOTION: NEGLIGIBLE
AMBIENT TEMPERATURE: 72° F
AMBIENT PRESSURE: 30"Hg
SHORE BASED VTO CAPABILITY: 16500

FIGURE 7

LATERAL INSTABILITY IN GROUND EFFECT



● REQUIREMENT

ROLL ATTITUDE STABILIZATION

TID-A-3159-V

FIGURE 8

AV-8A FLIGHT 51 FDR

DAY/VFR ANGLE DECK - VL
LOADING: FIGHTER WITH IFR PROBE
WOD: 41 KT
SHIP MOTION: NEGLIGIBLE

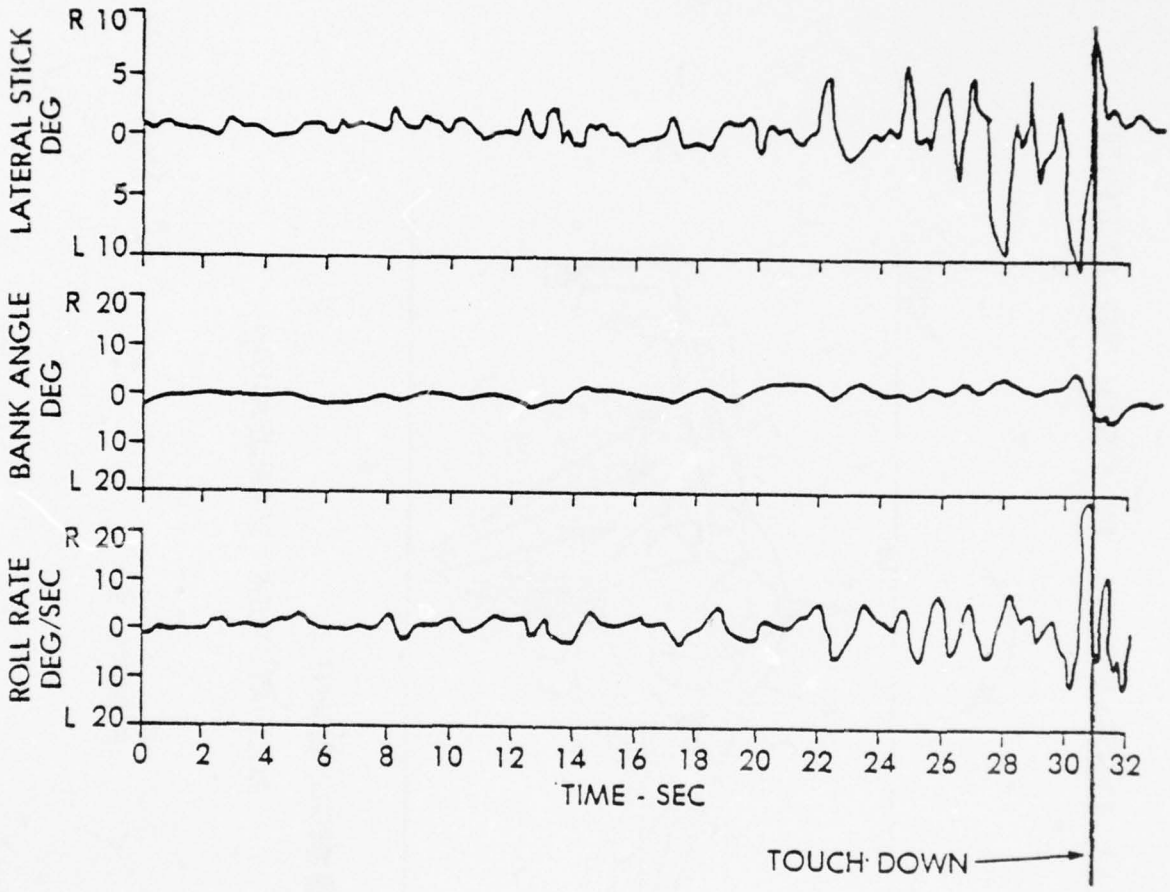


FIGURE 9

AD-A047 961 NAVAL AIR SYSTEMS COMMAND WASHINGTON D C F/G 1/3
PROCEEDINGS OF NAVY/NASA VSTOL FLYING QUALITIES WORKSHOP, HELD --ETC(U)
AUG 77 C J MAZZA, D M LAYTON, L V SCHMIDT

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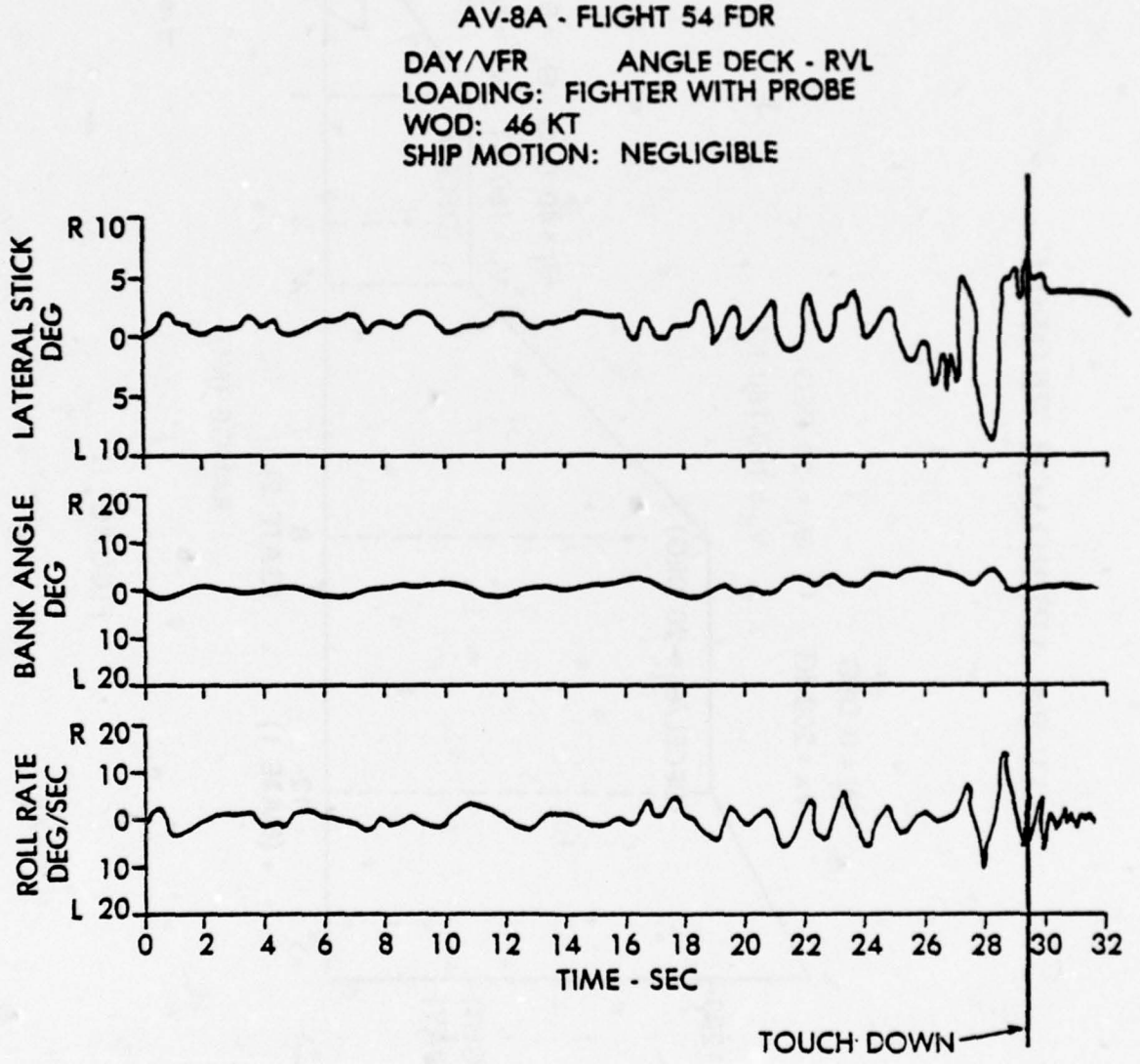
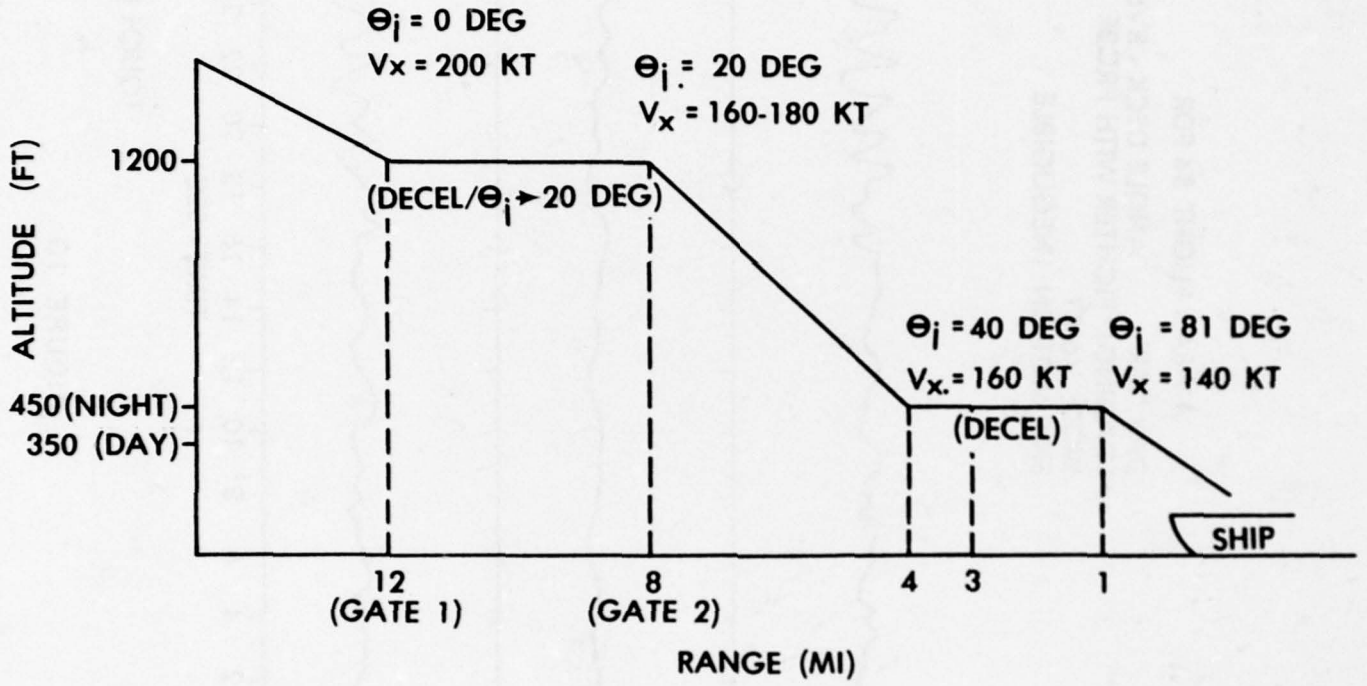

AV-8A - FLIGHT 54 FDR
DAY/VFR ANGLE DECK - RVL
LOADING: FIGHTER WITH PROBE
WOD: 46 KT
SHIP MOTION: NEGLIGIBLE
LATERAL STICK DEG
R 10
5
0
5
L 10
BANK ANGLE DEG
R 20
10
0
10
L 20
ROLL RATE DEG/SEC
R 20
10
0
10
L 20
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32
TIME - SEC
TOUCH DOWN

FIGURE 10

AV-8A APPROACH PROFILE



710-A-3170-V

FIGURE II

AV-8A FLIGHT 42 FDR

NIGHT/CCA LEVEL 400 FT
LOADING: ATTACK
SHIP MOTION: NEGLIGIBLE
TASK: VARIABLE HEADING

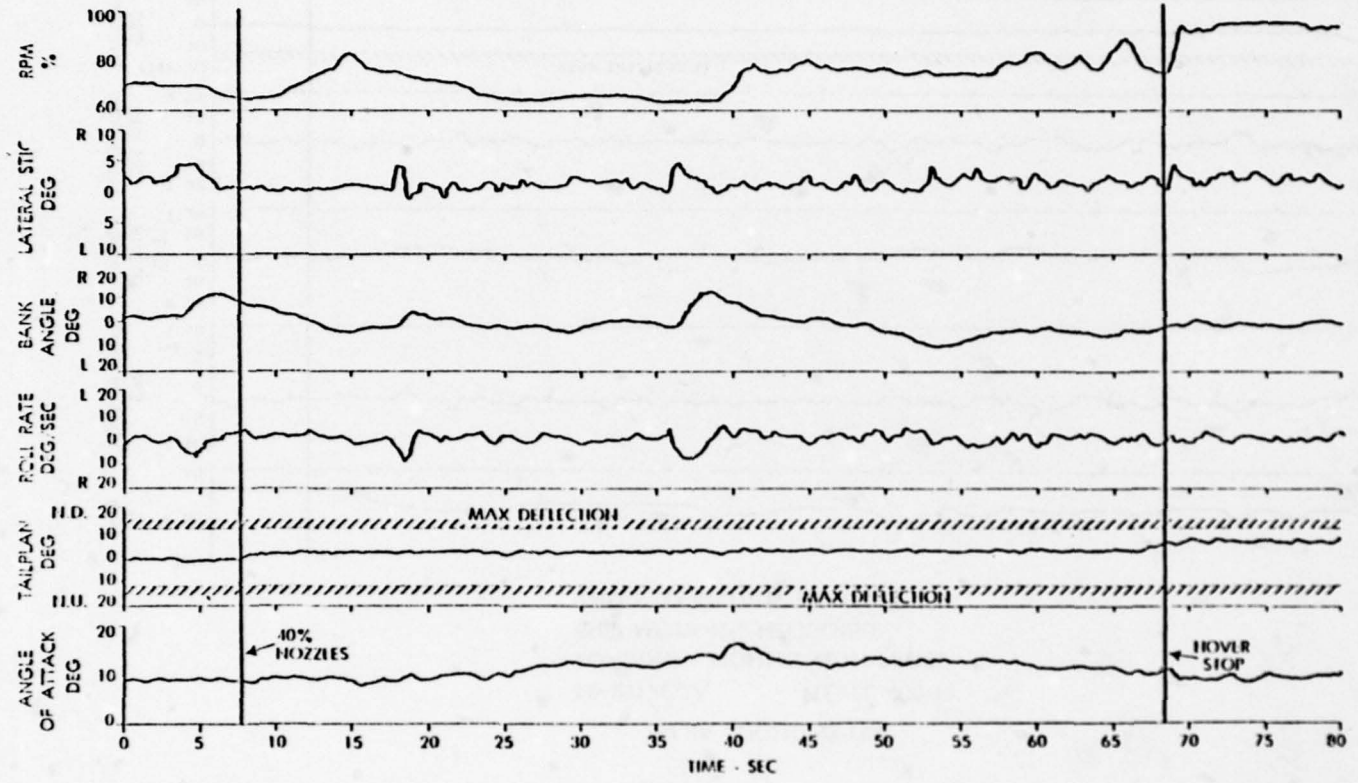


FIGURE 12

AV-8A FLIGHT 53 FDR

NIGHT/CCA LEVEL 400 FT
LOADING: FIGHTER WITH PROBE
SHIP MOTION: NEGLIGIBLE
TASK: CONSTANT HEADING

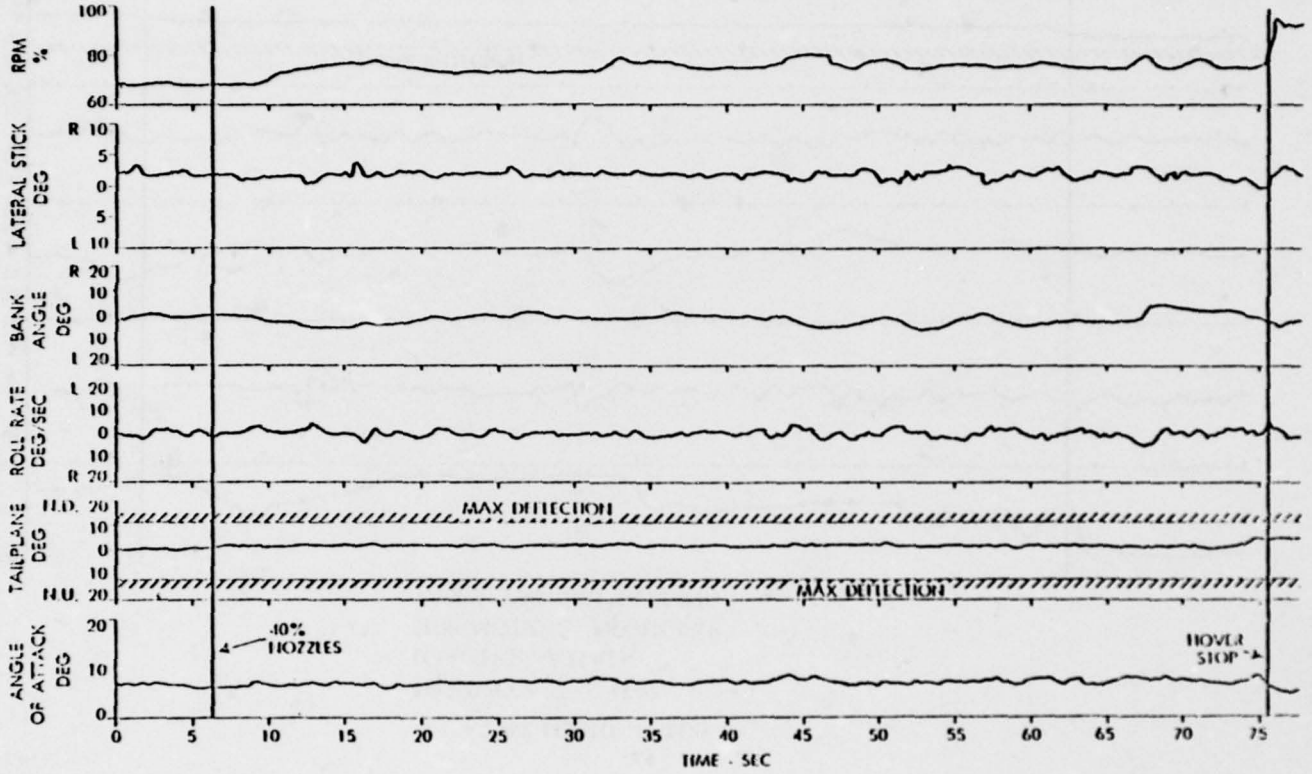


FIGURE 13

STABILITY AND CONTROL

A. FLIGHT CONTROL SYSTEM REQUIREMENTS

- ENSURE CAPABILITY OF:
  - ALL OPERATIONAL TASKS
  - W.O.D. UP TO 45 KTS INTO WIND
  - CROSS WIND COMPONENTS OF 25-30 KTS
- CONTROL MARGINS REQUIRED
  - 20-30% ABOVE STABILIZATION AND TASK LEVELS
  - ABOUT ALL AXES

FIGURE 14

B. STABILITY AUGMENTATION SYSTEM

- TO ENSURE:
  - CCA TO 200' AND $\frac{1}{2}$ NM
  - SPEED 60-90 KIAS
  - ACHIEVE HOVER WITHIN $\frac{1}{2}$ NM
  - SINGLE THRUST VECTOR CONTROL CHANGE
    - CRITICAL RECOVERY LOADING
    - IMC SEMI JET BORNE REQUIRED
    - IMC HOVER NOT REQUIRED

FIGURE 15

DISCUSSION

Mike Eden: Is there anything that you think could be gained by moving the nozzles to another setting when you're sinking towards the water? Is there like an increase in G to be stopped quickly in order to avoid sinking?

LTCOL Iles: Longitudinal acceleration will hurt you there. You decelerate, then you run out of tail plane and the next thing, the airplane's pitching up.

Duane Simon: Can you give us a quick relationship between jet sheet effect and your lateral stability?

Bob Traskos: Bud, I think you might wait until the next paper because I believe Mr. Fortenbaugh is going to talk to that subject.

Iles: I won't go into that now, but I can answer it for you later or, at least, show you some things on it. What I would like to do now is respond to some earlier questions concerning HUD's, a question was: What do we need? I think this has been identified in various technical papers. We need to be able to reduce our scan work load so we can handle any instabilities that might be present particularly in a failure mode case. The HUD needs to be able to provide us not only with operating point, but thrust-jettison trend information and envelope and systems warning and flight director data. This is something that might do it. (Shows chart). Possibly this could be masked. This is the envelope warning system. This circle here may not be a circle or whatever and it may not need to be presented on the HUD; but it tells us when we're approaching a critical parameter with our velocity vectors, flight director display, air speed trend status, thrust vector angle, VY information, engine information, VZ information, heading information, and pitch and roll attitude information.

Anon: Col Iles, you mentioned that flying angle of attack wasn't the way to go. Would you care to comment on that?

Iles: What I'm, talking about is flying angle of attack on post launch during a short take-off because the angle of attack is a function of flying performance and to get repeatability of task and performance, we need to be able to fly a precise attitude cue.

ANALYSIS OF THE INFLUENCE OF THE OGE/IGE TRANSITION ON VAK-191B FLYING QUALITIES IN HOVER

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Introduction

The VAK-191B program made extensive use of a ground-based hover test rig which allowed full scale power-on testing of the hover characteristics of the airplane (reference (a)). The rig or pedestal is fixed to the ground which prevents longitudinal and lateral translation; rotation about all aircraft axes and limited vertical travel are provided. The frequency response data obtained with the aircraft installed in this rig are the basis for this IGE (in ground effect) analysis of the VAK-191B. The limited vertical travel of the pedestal was not sufficient to test the aircraft OGE (out of ground effect) so that equivalent OGE pedestal frequency response data are not available.

Single axis pitch and roll frequency response data were taken with the VAK-191B control system in the VTOL mode. This mode has proportional attitude command in each axis. Therefore, while the pitch axis input command was oscillated, the roll control system attempted to hold wings level and, similarly, while the roll axis input command was oscillated, the pitch control system attempted to maintain a reference attitude. The yaw axis of the pedestal was locked for these tests because the aircraft yaw control system is rate command in all modes and would allow aircraft heading to drift in the presence of yaw moment disturbances.

Analysis of the roll response data which produced quantification of the IGE propulsion-induced roll angle effect on the aircraft and subsequent analysis of the influence of this effect on roll flying qualities are described. Validity of the analytical flying qualities results and the IGE and OGE roll models is established by comparison with VAK-191B operational limitations and pilot comments on the aircraft's handling characteristics. A similar analysis of the pitch response data was made and figures summarizing these results are included in the Appendix to this paper.

Frequency Response Analysis

Figure 1 is a functional diagram of the VTOL mode of the VAK-191B roll flight control system. (Control system details are given in reference (a).) In this mode lateral motion of the cockpit control stick commands roll attitude (ϕ_c) proportional to stick deflection. The system is fully fly-by-wire with no limiting of feedback authority. The transfer relation between aircraft roll angle (ϕ) and roll moment (M_{cr}) inputs is designated "pedestal/aircraft roll dynamics" because of the inability to isolate pedestal and aircraft dynamic responses from the frequency response data.

The intent of the frequency response analysis was to seek correlation between VFW-Fokker control system background data and the measured pedestal

data. Since the characteristics of all elements in figure 1 except the pedestal/airframe roll dynamics could be and were determined with a high degree of confidence in laboratory situations, the first step in the analysis was to establish a model for the pedestal/airframe roll dynamics. (Note that since M_{c_r} is proportional to duplex servo output (δ_{DS}) and M_{c_r} is not measurable, pedestal/airframe dynamics can also be represented as ϕ/δ_{DS}.) This was accomplished as follows:

1. A frequency response for the ϕ to δ_{DS} transfer characteristics was determined from the pedestal data (see data points on figure 3). It was observed on the time traces that the ϕ and δ_{DS} waveforms were only slightly distorted from pure sinusoids; this indicated that a linear model could reasonably represent the ϕ to δ_{DS} transfer characteristics.

2. Since the aircraft is IGE when installed on the pedestal, the fountain and flow entrainment characteristics depicted in figure 2 were examined. It is evident that an unstable propulsion-induced roll moment due to roll angle (L_ϕ) may be present; right wing down causes the fountain to move with respect to the aircraft in a direction which produces a right wing down moment; also the reduced clearance between right wing tip and the ground causes reduced pressure on the underside of the wing and a resultant right wing down moment. A roll moment due to roll rate (L_p) may also be present but could not be observed within the limits of the data as indicated by the next consideration.

3. The phase of the ϕ to δ_{DS} response determined in step 1 deviated only slightly from 180 degrees throughout the frequency range of the pedestal data (1.7 to 9.0 rad/sec) shown on figure 3. If an L_p were present, the phase would have deviated significantly from 180^o through some frequency range; so it was concluded that the available data did not support the presence of L_p.

4. It is assumed herein that at zero airspeed (which the pedestal data represent) and OGE the ϕ to δ_{DS} transfer characteristics are

$$\left.\frac{\phi}{\delta_{DS}}\right|_{OGE} = \frac{K_{BS_r}}{I_x s^2} \qquad (1)$$

where s = Laplace variable

I_x = VAK-191B roll inertia = 3140 slug ft^2

K_{BS_r} = VAK-191B bleed system gain = 57.0 ft-lb/% δ_{DS}

This transfer function has 180^o phase at all frequencies and thus matches the measured phase data. The measured gain data follow the $1/s^2$ trend at high frequencies but tend towards a finite D.C. value (figure 3). This deviation supports the presence of propulsion-induced effects IGE which are not present OGE.

5. After considering all the above observations it became evident that the ϕ to δ_{DS} dynamics could be represented by a second order system with ϕ feedback and no damping:

$$I_x\ddot{\phi} = K_{BS_r}\ \delta_{DS} + L_\phi\ \phi \qquad (2)$$

where L_ϕ is greater than zero and must be determined

6. Fitting the pedestal data with various L_ϕ's resulted in L_ϕ = 450 ft-lb/deg and the following ϕ to δ_{DS} transfer function:

$$\frac{\phi}{\delta_{DS}} = \frac{-0.114}{(-0.35s+1)(0.35s+1)} \qquad (3)$$

Figure 3 demonstrates the excellent fit accorded by this relatively simple model.

The second step in the frequency response analysis was to calculate the closed loop ϕ/ϕ_C characteristics and compare then with the measured characteristics. OGE and IGE ϕ/ϕ_C frequency responses were calculated using equations (1) and (3), respectively, with the transfer functions given in figure 1 for the remaining loop elements. The results are shown in figure 4. Note that there is a significant difference between OGE and IGE characteristics. Note also that the calculated IGE characteristics provide an excellent match of the measured magnitudes and a good match of the measured phases. An excellent phase match is obtained if a 0.06 dead time between ϕ and ϕ_C is assumed; this is not an unreasonable assumption in view of the fact that the actual frequency response was determined from strip chart data.

Summarizing the VAK-191B roll axis frequency response analysis supports the use of a simple second order model with no rate feedback and unstable attitude feedback (equation (2)) to represent the IGE roll dynamics (more specifically the pedestal/aircraft dynamics) of the unaugmented airplane. The significant differences between IGE and OGE dynamics can now be examined in terms of the roll flying qualities changes which occur in the OGE to IGE transition and vice versa.

Model for IGE/OGE Flying Qualities Analysis

Figure 5 is a model for manual control of the lateral position of the VAK-191B in hover. This model was analyzed to quantify the changes in system dynamics, pilot compensation, and control power usage which occur in the OGE/IGE transition. The VAK-191B roll attitude control system detailed in figure 1 was given the equivalent form shown in figure 5 by neglecting the high frequency duplex servo dynamics, combining the roll angle and roll rate feedback paths, neglecting the stick shaping network dynamics because of the near cancellation of the pole and zero, and inserting the IGE and OGE representations for the unaugmented airplane established by the frequency response analysis. A disturbance roll moment (L_{DIST}) was included to represent random roll moment inputs which arise from sources such as atmospheric or ship airwake turbulence or control cross-coupling. The displayed information (ΔY) represents the information required by the pilot to maintain lateral position;

this information may be obtained by viewing the outside world or a cockpit display. Note that lateral acceleration is proportional to roll attitude in hover and the lateral position (Y) to ϕ dynamics can be represented as a K/s^2.

Controlled Element Changes

The controlled element (i.e., that controlled by the pilot) in figure 5 is the VAK-191B with its ϕ to ϕ_c and $\dot{\phi}$ to ϕ_c control loops closed. A root locus comparison of these loop closures OGE and IGE is given by figure 6. Since the control system characteristics do not change in transitioning between OGE and IGE the loops are closed with the same root locus gain. The effect of the unstable roll angle feedback IGE is to move the open loop airframe poles from the origin OGE to $\sigma = \pm 2.86$ rad/sec IGE. This in turn causes a significant change in the controlled element root locus and the ϕ/ϕ_c closed loop roots; the dominant roots move from $\zeta = 0.87$, $\omega_n = 2.75$ rad/sec OGE to $\zeta = 0.58$, $\omega_n = 0.34$ rad/sec IGE. In transfer function format, the OGE and IGE ϕ/ϕ_c dynamics are as follows:

$$\left(\frac{\phi}{\phi_c}\right)_{OGE} = \frac{9.51(s+0.44)}{(s+0.55)\left[s^2+2(0.87)(2.75)s+2.75^2\right]} \tag{4}$$

$$\left(\frac{\phi}{\phi_c}\right)_{IGE} = \frac{9.51(s+0.44)}{(s+4.93)\left[s^2+2(0.58)(0.34)s+0.34^2\right]} \tag{5}$$

Equations (4) and (5) define the controlled element OGE and IGE respectively.

Pilot Compensation Considerations

POR (Pilot Opinion Rating) is correlated with the degree of compensation that must be effected by a pilot to perform a given task with a specific controlled element according to the following principle: the more gain, lead, or higher order compensation required by the pilot, the higher will be the POR and the poorer will be the flying qualities of the controlled element. The change in pilot compensation (ΔY_{P_R}) required to maintain constant lateral positioning performance when transitioning from OGE to IGE is given by:

$$\Delta Y_{P_R} = \frac{(\phi/\phi_c)_{OGE}}{(\phi/\phi_c)_{IGE}} = \frac{(s+4.93)\left[s^2+2(0.58)(0.34)s+0.34^2\right]}{(s+0.55)\left[s^2+2(0.87)(2.75)s+2.75^2\right]} \tag{6}$$

This assumes that the pilot provides compensation when entering ground effect which will maintain a constant $Y/\Delta Y$ transfer function (see figure 5) or, equivalently, constant Y/Y_c closed loop performance.

The frequency response of ΔY_{P_R} is plotted in figure 7. The response indicates that the pilot must reduce his OGE gain by a factor of 10 and produce a second order lead in order to maintain constant lateral positioning performance IGE. These required compensation changes support the conclusion that the VAK-191B exhibits degraded lateral flying qualities upon transitioning from OGE to IGE.

The U.S. Marine Corps pilot for the VAK-191B flight test program records in reference (a) the following observations concerning the aircraft's lateral flying qualities:

1. In hover OGE a PIO (Pilot Induced Oscillation) could be produced by trying to maintain tight control of lateral position.

2. The technique adopted for vertical landing was to establish a hover OGE over the desired landing spot and let down without correcting for lateral drift.

The second observation which indicates pilot reluctance to enter the loop (i.e., he adopts a low gain) while IGE is partially supported by the ΔY_{p_B} analysis which indicated a large reduction in pilot gain required for IGE conditions. Both observations can be fully appreciated by referring to figure 8 which depicts root loci of the manual Y to Y_e loop closures both in and out of ground effect.

The inclusion of the Y/ϕ and ϕ/ϕ_c poles and zeros on the root loci is obvious; the inclusion of the zero at $\sigma = -1/\tau_L$ is not obvious. It can be shown (reference (b)) that an effective outer guidance loop closure can be obtained by simply feeding back position and position rate for systems meeting the following criteria:

1. Acceleration control is obtained by attitude

2. The attitude control bandwidth is wider than the guidance loop bandwidth.

3. Control coupling and dynamic coupling among the various degrees of freedom have been minimized by inner loops.

The lateral position control of a V/STOL airplane in general and the VAK-191B OGE in particular meets these criteria, therefore the zero has been added to figure 8 to show the position plus position rate feedback. This lead may be pilot-generated or generated by display "quickening". The lead has been arbitrarily placed to the left of the ϕ/ϕ_c pole at $\sigma = -0.55$ rad/sec on the OGE root locus and, similarly, to the left of the ϕ/ϕ_c zero at $\sigma = -0.44$ rad/sec on the IGE root locus.

Recall the first pilot observation while considering the OGE root locus in figure 8. The locus high gain asymptotes are such that the system can exhibit instability (i.e., PIO) if the pilot gain becomes too high. With $1/\tau_L$ assumed equal to 0.75 rad/sec the locus enters the right half plane (becomes unstable) at $j\omega = 2.14$ rad/sec with a pilot gain of 3.08 deg/ft. If the pilot becomes aggressive and increases his lead to $1/\tau_L = 0.20$ rad/sec, the character of the locus changes and the system becomes unstable at $j\omega = 2.68$ rad/sec with a pilot gain of 1.30 deg/ft. The locus changes in that the branches originating at the ϕ/ϕ_c oscillatory poles do not coalesce at the σ axis but drift towards the right half plane and define the stability of the system. The fact that the lateral position loop can go unstable and does so at a lower gain under conditions of increased pilot aggressiveness supports the pilot observation that he could produce PIO by trying to maintain tight lateral position control.

The IGE locus indicates that the lateral position loop becomes unstable at an extremely low gain and frequency (specifically, $j\omega$ = .08 rad/sec, and pilot gain = 0.0016 deg/ft) and does not regain stability. This means that any half-hearted attempt by the pilot to close the loop would result in PIO which supports the second pilot observation that he did not correct for lateral drift IGE.

Roll Control Power Considerations

The IGE and OGE lateral control models (figure 5) were compared on the basis of control power required for maneuvering, regulation of random disturbances, and trimming in a crosswind. Maneuvering control power was determined (see figure 9 for the equations) by calculating the magnitude of a step input in L_c which would produce 6 degrees of roll angle in 1 sec. This requirement was taken from the Navy Type A V/STOL Request for Information specification. Control power required for controlling random disturbances was obtained (see figure 9 for the equations) by assuming a form for the power spectral density of L_{DIST} ($\Phi_{L_{DIST}}$) and then calculating the RMS L_c ($\overline{L_c^2}$) required as a function of the standard deviation of L_{DIST} ($\sigma_{L_{DIST}}$) and the input spectrum bandwidth (ω_j). Control power required for trimming in a crosswind was determined (see figure 10 for the equations) by calculating the roll angle required to trim (ϕ_{TRIM}) a sideforce ($Y_{v_{CW}}$) due to a side velocity (v_{CW}) then calculating the control power required to trim the roll moment ($I_x \dot{\phi}_{CW}$) due to the same side velocity.

Control powers for maneuvering and controlling disturbances are compared on figure 11. The first shows normalized control power (i.e., roll acceleration) for OGE and IGE as a function of ω_j and $\sigma_{\ddot{\phi}_{DIST}} = \frac{\sigma_{L_{DIST}}}{I_x}$. The maximum available VAK-191B roll control power is included for reference. The OGE and IGE control powers for maneuvering are approximately the same with OGE being about 6% higher than IGE. There is a significant difference between the OGE and IGE control powers required for disturbance regulation, the ratio between IGE and OGE requirements varying from approximately 2.0 at high ω_j to 7.0 at low ω_j. This result when compared with available VAK-191B control power correlates with pilot comments (reference (a)) that in close proximity to the ground in any wind at all the cockpit indicator for available roll control power frequently indicated little if any left. The tie between pilot comment and analytic result is that the automatic portion of the VAK-191B roll control system has 100% authority and was using most of the control power for disturbance regulation leaving little for pilot inputs.

Control powers for trimming in a crosswind are compared on figure 10. The figure shows control power required to trim side acceleration due to a side gust as a function of side acceleration (or equivalently ϕ_{TRIM}) and roll acceleration due to the same gust. Implicit in this presentation is a comparison of the effects of rolling moment due to sideslip (L_β) and side force due to sideslip (Y_β) on roll control power for constant side gust inputs. The effect of the propulsion-induced roll moment due to roll angle (L_ϕ) IGE is to couple the trim sideforce and roll equations. As can be seen, $L_\phi \phi_{TRIM}$ is a significant contributor which would use all available control power if ϕ_{TRIM} is greater than 12 to 15 degrees.

Conclusions

The analysis of the influence of OGE/IGE transition on VAK-191B lateral flying qualities in hover based on roll frequency response data taken in ground effect has resulted in the following conclusions:

1. An unstable propulsion-induced roll moment due to roll angle of approximately 450 ft-lb/deg is produced when the VAK-191B operates in ground effect. This effect is not present out of ground effect.

2. Good correlation with measured frequency response data was obtained with a simple model of the roll angle (ϕ) to duplex servo (δ_{DS}) dynamics of the VAK-191B.

3. Results based on an analysis of a simple model for manual control of lateral position supported several observations of VAK-191B pilots concerning lateral flying qualities and indicated that trimming in a crosswind and regulating disturbances when in ground effect could easily require all available roll control power.

References

(a) VAK-191B Joint Flight Test Program Final Report, NAVAIRSYSCOM Report to be issued May 1977.

(b) Dukes, Theodore A., Helicopter Station Keeping, ECOM Technical Report 02412-9, September 1972.

VAK-191B ROLL CONTROL SYSTEM
VTOL MODE

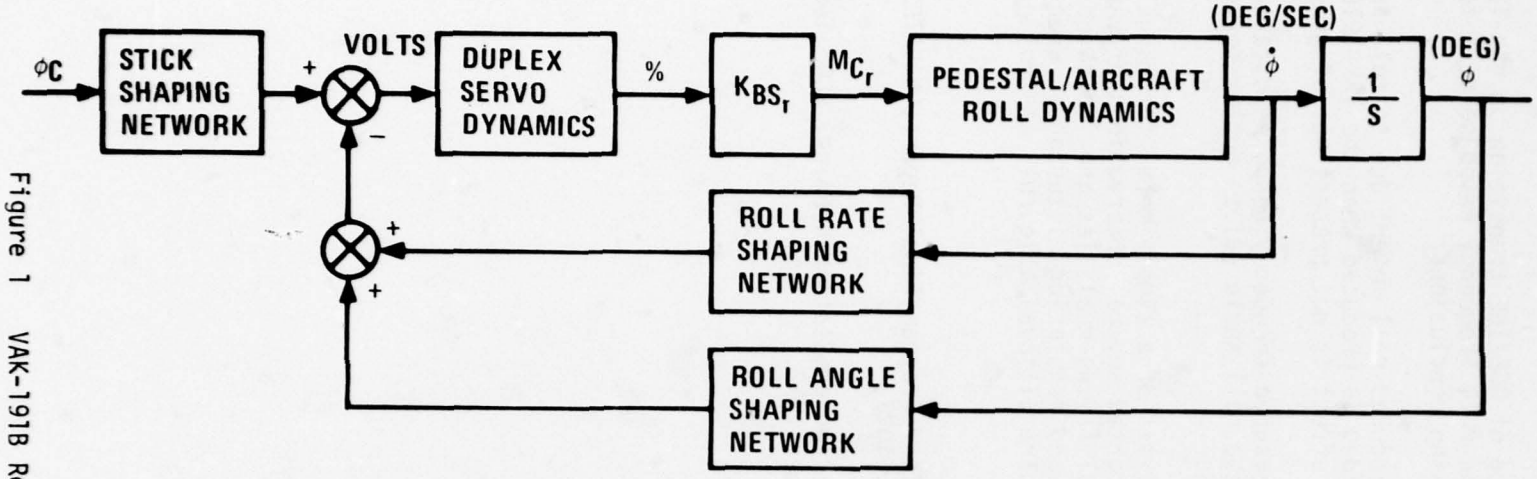


Figure 1 VAK-191B Roll Control System VTOL Mode

G_{PA_r} = PEDESTAL/AIRCRAFT ROLL DYNAMICS

$= \frac{-0.114s}{(0.35s + 1)(-0.35s + 1)}$ DEG/SEC/%

G_{ST_r} = STICK SHAPING NETWORK

$= \frac{0.88(2.085s + 1)}{(2.29s + 1)}$ VOLTS/DEG

$G_{\dot{\theta}}$ = ROLL RATE SHAPING NETWORK

$= \frac{0.58(1.8s + 1)}{(2.29s + 1)}$ VOLTS/DEG/SEC

G_{θ} = ROLL ANGLE SHAPING NETWORK

$= \frac{0.88(1.8s + 1)}{(2.29s + 1)}$ VOLTS/DEG

G_{DS} = DUPLEX SERVO DYNAMICS

$= \frac{11.63}{\frac{s^2}{23.02^2} + \frac{2(0.89)}{23.02}s + 1}$ %/VOLT

K_{BS_r} = 51.0 FT-LB/%

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VAK-191B FOUNTAIN CONFIGURATION

FRONT VIEW

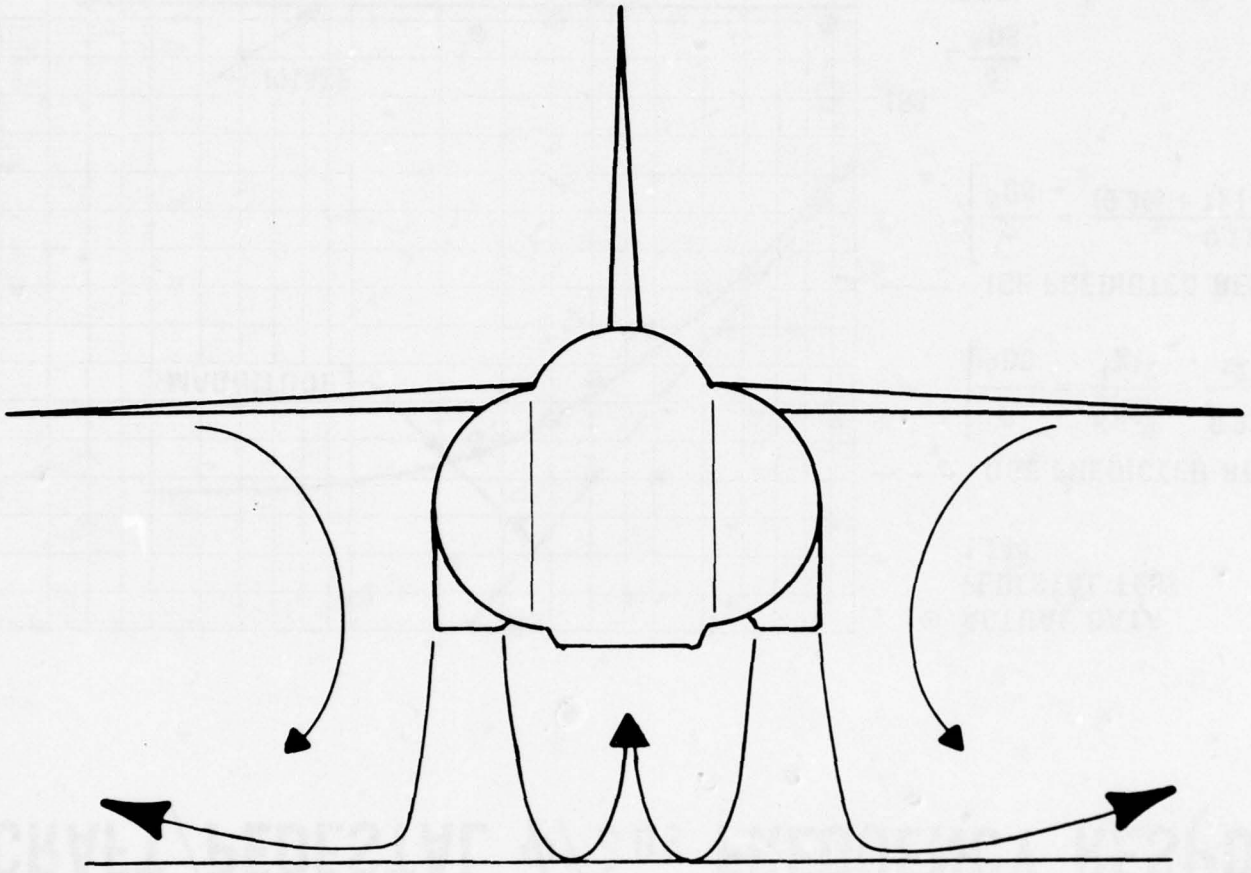
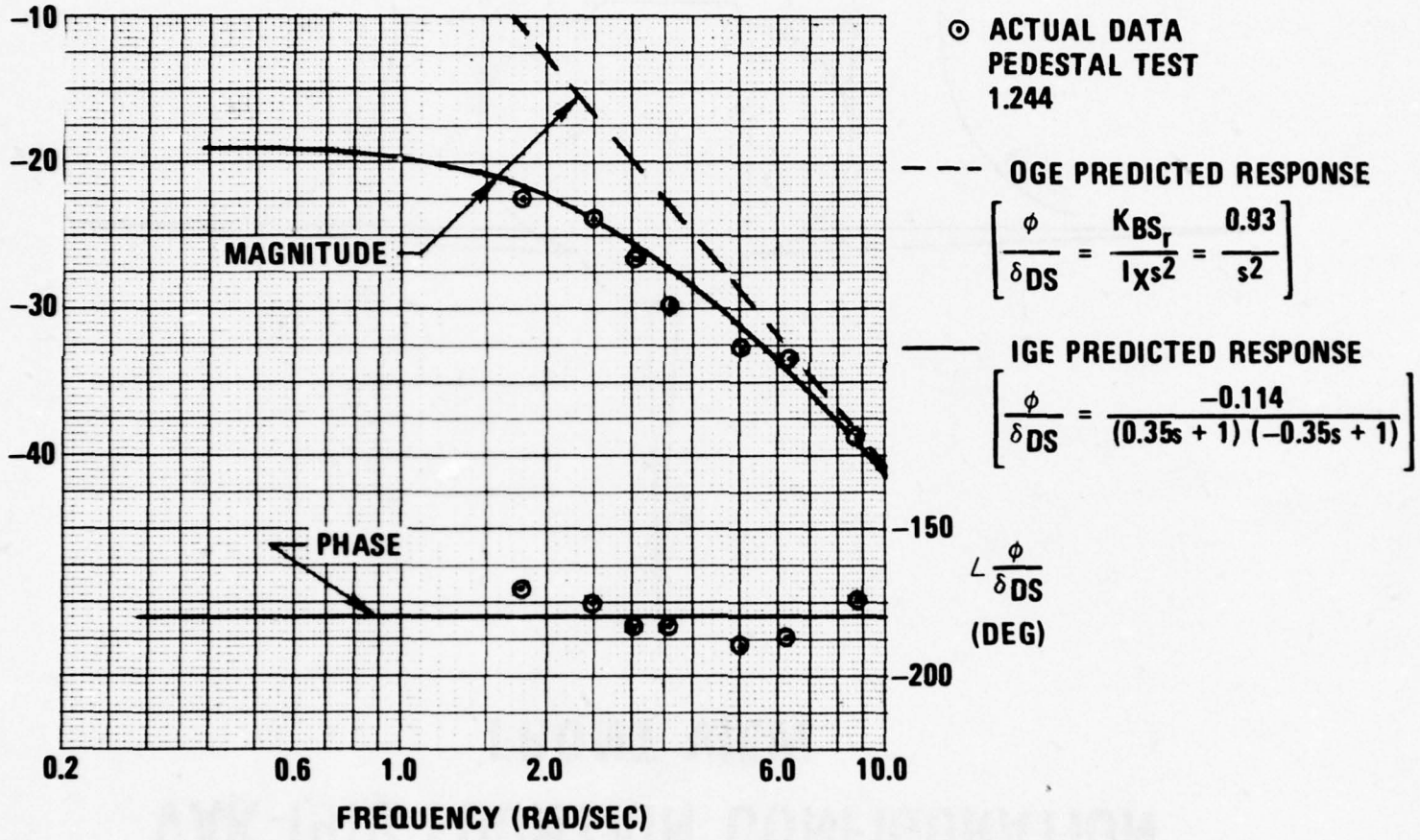


Figure 2 VAK-191B Fountain Configuration (Front View)

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AIRCRAFT/PEDESTAL ϕ/δ_{DS} FREQUENCY RESPONSE



P7-383-16

Figure 3 Aircraft/Pedestal ϕ/δ_{DS} Frequency Response

CLOSED LOOP ϕ/ϕ_C FREQUENCY RESPONSE

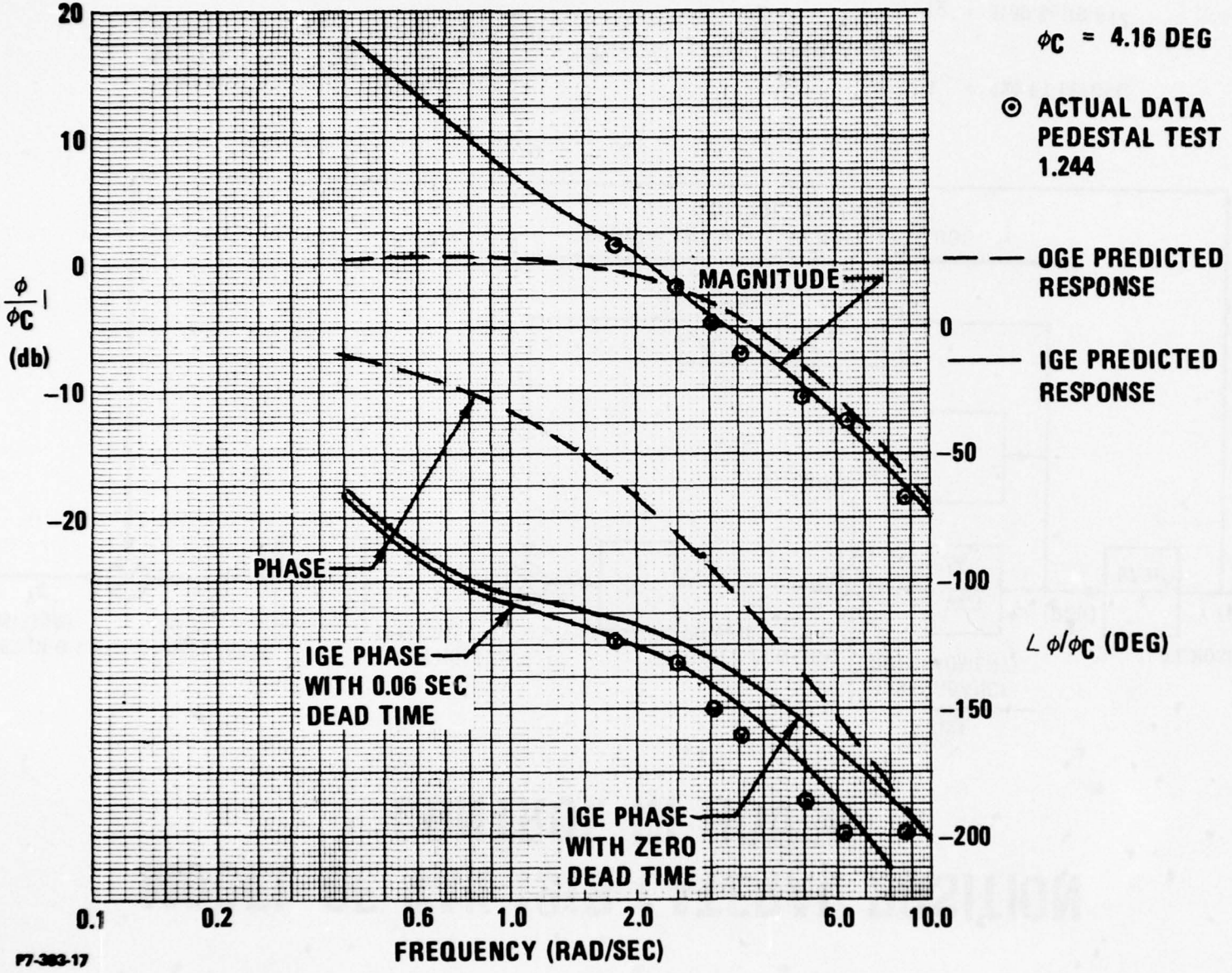
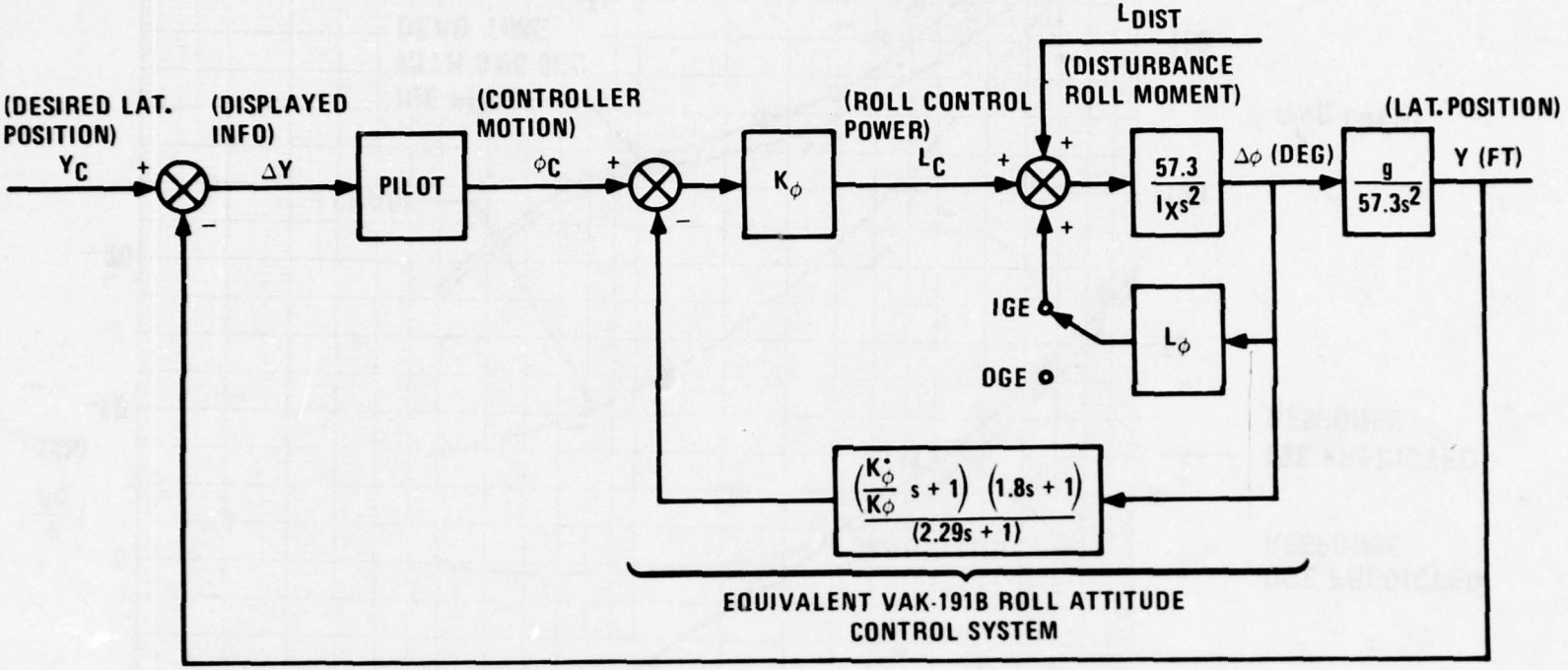


Figure 4 Closed Loop ϕ/ϕ_C Frequency Response

MODEL OF VAK-191B LATERAL POSITION CONTROL IN HOVER



CONTROL SYSTEM GAINS

$K_\phi^* = 521.3$ FT-LB/DEG

$K_\phi = 342.5$ FT-LB/DEG/SEC

IGE FEEDBACK

$L_\phi = 450$ FT-LB/DEG

$I_X = 3140$ SLUG-FT^2

P7-393-9

Figure 5 Model of VAK-191B Lateral Position Control in Hover

DIFFERENCE IN VAK-191B CONTROLLED ELEMENT CHARACTERISTICS IN GROUND PROXIMITY

ROOT LOCUS COMPARISON OF ROLL ATTITUDE CONTROL

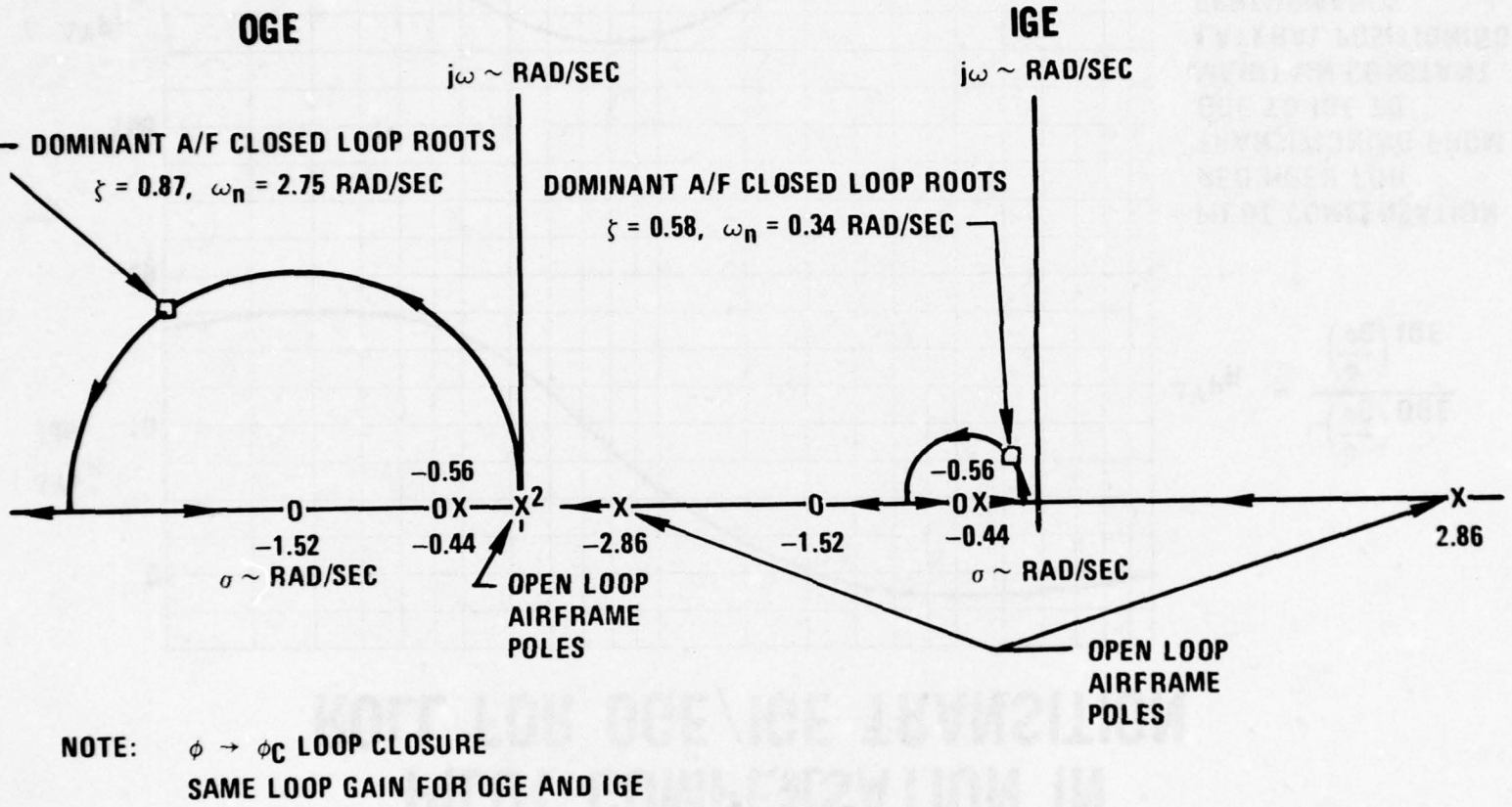
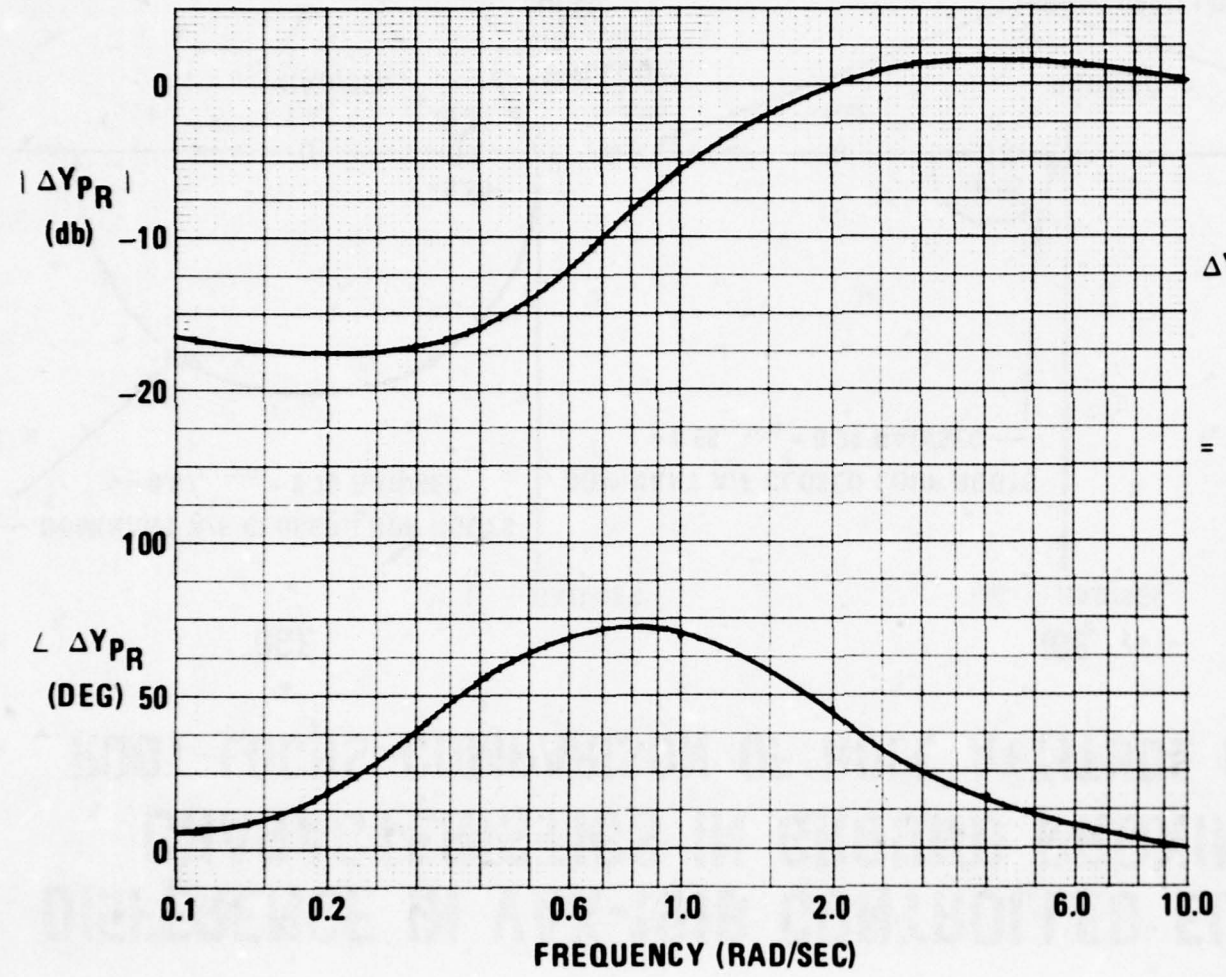


Figure 6 Difference in VAK-191B Controlled Element Characteristics in Ground Proximity - Root Locus Comparison of Roll Attitude Control

PILOT COMPENSATION IN ROLL FOR OGE/IGE TRANSITION



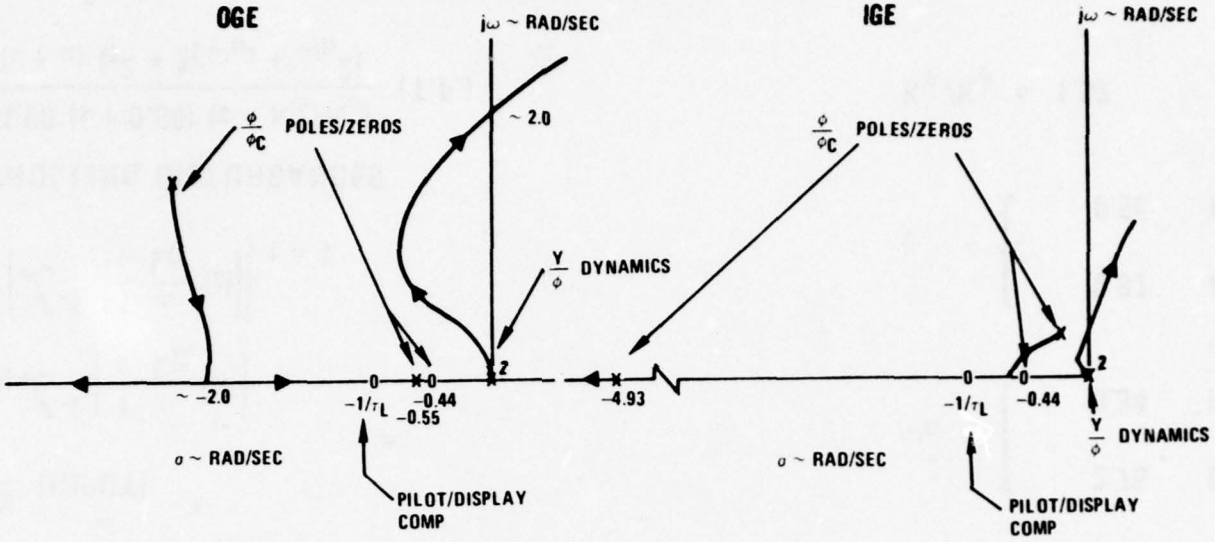
$$\Delta Y_{P_R} = \frac{\left(\frac{\phi}{\phi_C}\right)_{OGE}}{\left(\frac{\phi}{\phi_C}\right)_{IGE}}$$

= PILOT COMPENSATION REQUIRED FOR TRANSITIONING FROM OGE TO IGE TO MAINTAIN CONSTANT LATERAL POSITIONING PERFORMANCE

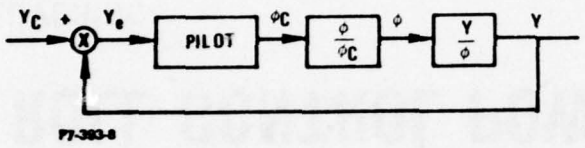
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Figure 7 Pilot Compensation in Roll for OGE/IGE Transition

MANUAL LATERAL POSITION CONTROL OF VAK-191B IN GROUND PROXIMITY
ROOT LOCUS COMPARISON



Y → Y_e LOOP CLOSURE



P7-393-8

GENERAL FORM OF ϕ/ϕ_C =

$$\frac{K\,(s + 0.44)}{(s + \alpha)\,(s^2 + 2\zeta\omega_n s + \omega_n^2)}$$

Figure 8 Manual Lateral Position Control of VAK-191B in Ground Proximity - Root Locus Comparison

ROLL CONTROL POWER EQUATIONS

C.P. FOR MANEUVERING

$$\frac{\phi}{L_C}(s) = \frac{0.0182\,(s + 0.44)}{(s + \alpha)\,(s^2 + 2\zeta\omega_n s + \omega_n^2)} \quad \text{(T.F.)}$$

$$L_C = \frac{L_{MAN}}{s} \quad \text{(INPUT)}$$

$$\phi(t) = L_{MAN}\,\mathcal{L}^{-1}\left[\frac{1}{s}\,\frac{\phi}{L_C}(s)\right]$$

$$L_{MAN} = \phi(1)/\left[\mathcal{L}^{-1}\left[\frac{1}{s}\,\frac{\phi}{L_C}(s)\right]\right]_{t=1}$$

$$\alpha = \begin{cases} 0.55 & \text{OGE} \\ 4.93 & \text{IGE} \end{cases}$$

$$\omega_n = \begin{cases} 2.75 & \text{OGE} \\ 0.34 & \text{IGE} \end{cases}$$

$$\zeta = \begin{cases} 0.87 & \text{OGE} \\ 0.58 & \text{IGE} \end{cases}$$

C.P. FOR CONTROLLING DISTURBANCES

$$\frac{L_C}{L_{DIST}}(s) = \frac{4.90\,(s + 0.56)\,(s + K_\phi/K_{\dot\phi})}{(s + \alpha)\,(s^2 + 2\zeta\omega_n s + \omega_n^2)} \quad \text{(T.F.)}$$

$$K_\phi/K_{\dot\phi} = 1.52$$

$$\Phi_{L_{DIST}}(s) = \frac{2\omega_i\,\sigma^2_{L_{DIST}}}{s^2 + \omega_i^2} \quad \text{(INPUT)}$$

$$\overline{L_C^2} = \frac{1}{2\pi j}\int_{-j\infty}^{j\infty} \frac{L_C}{L_{DIST}}(s)\,\frac{L_C}{L_{DIST}}(-s)\,\Phi_{L_{DIST}}(s)\,ds = I_X\overline{\ddot\phi_C^2}$$

P7-393-2

Figure 9 Roll Control Power Equations

ROLL CONTROL POWER FOR TRIMMING IN A CROSSWIND

OGE

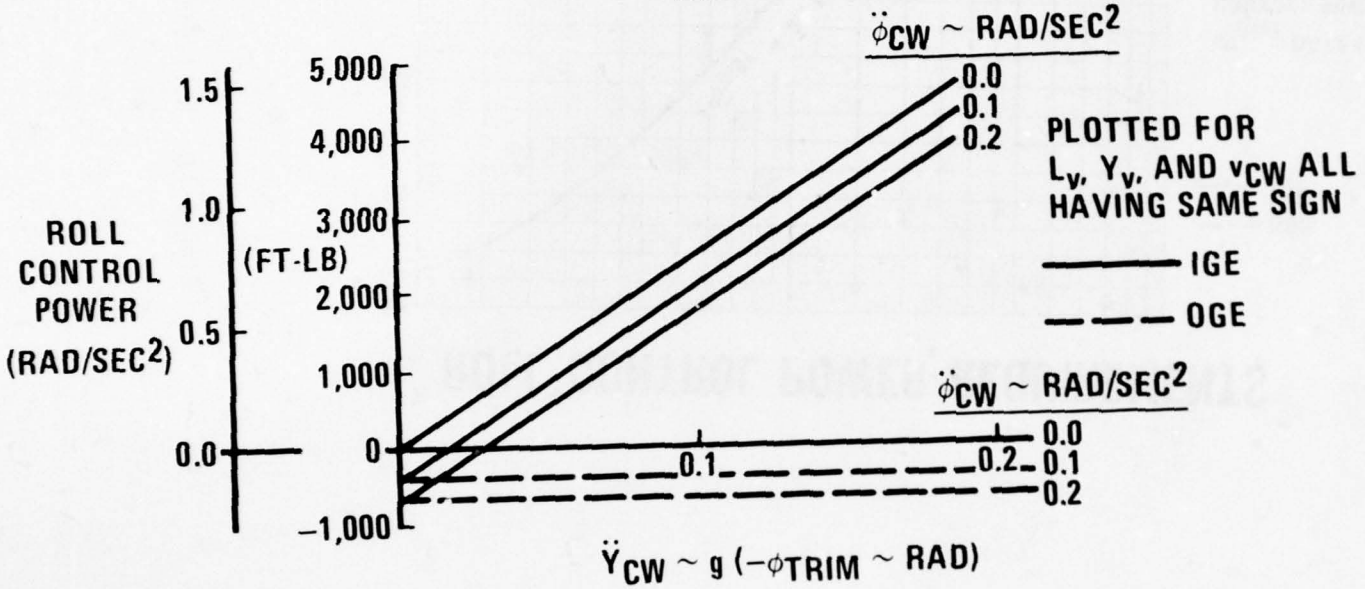
SIDEFORCE – $\ddot{Y}_{CW} + g\,\phi_{TRIM} = 0 \longrightarrow \ddot{Y}_{CW} = \frac{Y_v\, v_{CW}}{m}$

ROLL – $I_X\,\ddot{\phi}_{CW} + L_{C_{OGE}} = 0 \longrightarrow \ddot{\phi}_{CW} = \frac{L_v\, v_{CW}}{I_X}$

IGE

SIDEFORCE – $\ddot{Y}_{CW} + g\,\phi_{TRIM} = 0$

ROLL – $I_X\,\ddot{\phi}_{CW} + L_{C_{IGE}} + L_\phi\,\phi_{TRIM} = 0$



P7-393-24

Figure 10 Roll Control Power for Trimming in a Crosswind

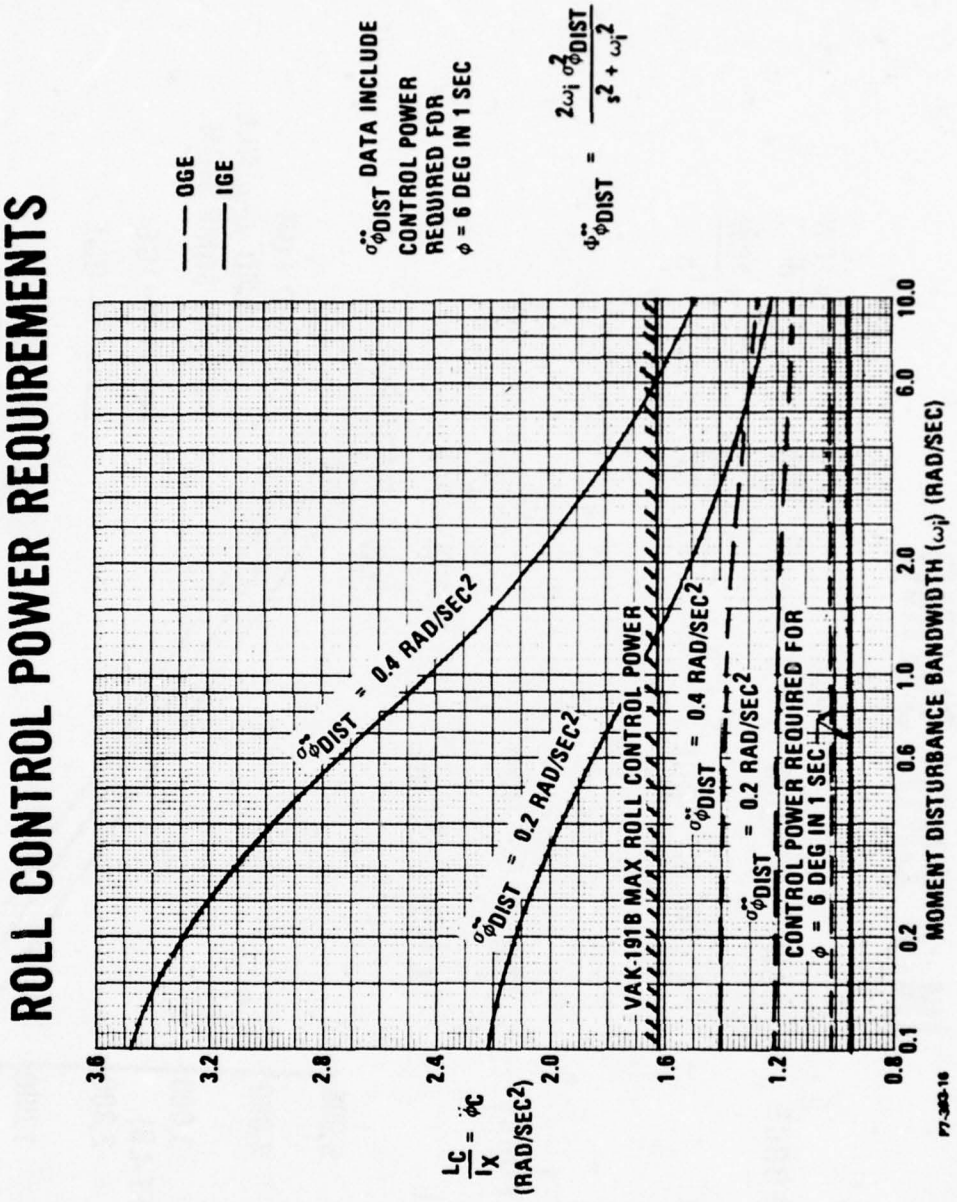
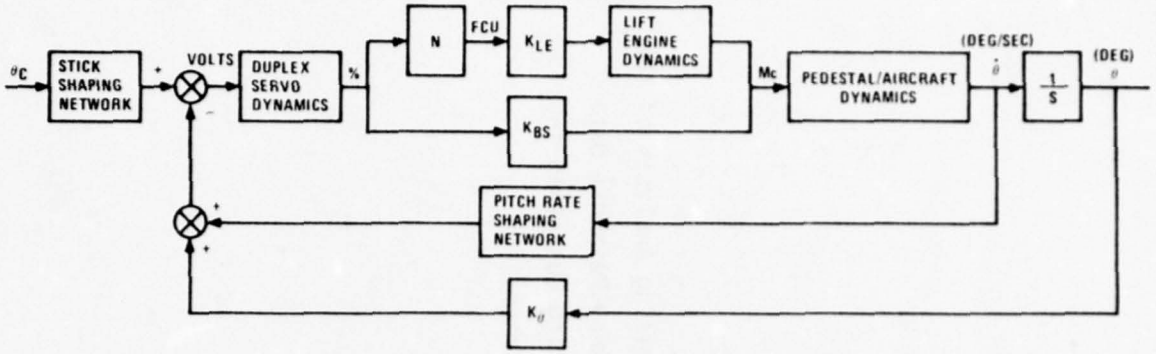


Figure 11 Roll Control Power Requirements

APPENDIX - Figures Summarizing Analysis of the VAK-191B Pitch Frequency Response Data and Longitudinal Flying Qualities in the OGE/IGE Transition

VAK-191B PITCH CONTROL SYSTEM
VTOL MODE



G_{PA} = PEDESTAL/AIRCRAFT DYNAMICS

$$= \frac{0.00403_{se}\cdot 0.04s}{\frac{s^2}{0.5^2} + \frac{2\,(0.5)}{0.5}s + 1} \text{ DEG/SEC/FT-LB}$$

N = DESCRIBING FUNCTION FOR THRUST MODULATION

G_{ST} = STICK SHAPING NETWORK

$$= \frac{0.87\,(1.190s + 1)}{(1.65s + 1)} \text{ VOLTS/DEG}$$

G_{DS} = DUPLEX SERVO DYNAMICS

$$= \frac{11.63}{\frac{s^2}{23.02^2} + \frac{2\,(0.89)}{23.02}s + 1} \text{ \%/VOLTS}$$

$G_{\dot{\theta}}$ = PITCH RATE SHAPING NETWORK

$$= \frac{0.61\,(0.078s + 1)}{(0.032s + 1)} \text{ VOLTS/DEG/SEC}$$

K_{θ} = PITCH ANGLE FEEDBACK = 0.87 VOLTS/DEG

K_{LE} = LIFT ENGINE GAIN = 859.6 FT-LB/DEG FCU

K_{BS} = BLEED SYSTEM GAIN = 235.8 FT-LB/%

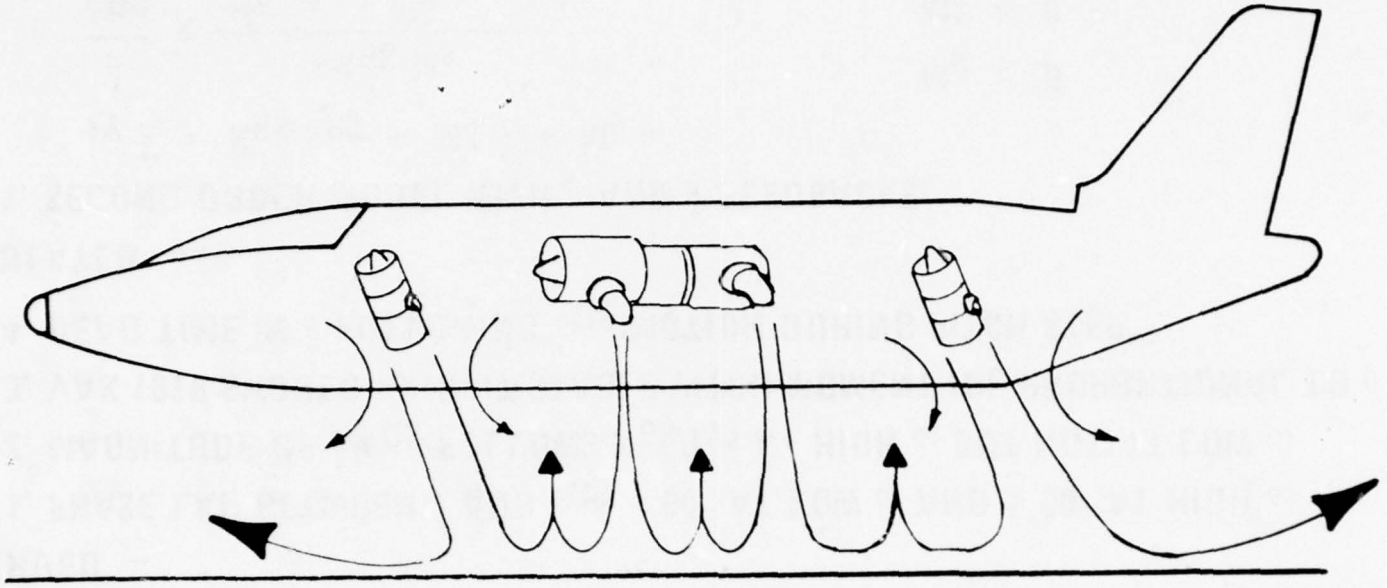
G_{LE} = LIFT ENGINE DYNAMICS

$$= \frac{1}{0.5s + 1} \text{ OR } \frac{1}{0.3s + 1}$$

P7-383-7

VAK-191B FOUNTAIN CONFIGURATION

SIDE VIEW



P7-393-23

AIRCRAFT/PEDESTAL PITCH MODEL DEVELOPMENT

- **OBSERVED –**
  1. PHASE LAG BETWEEN $\dot{\theta}$ AND $\delta_{DS} < 90°$ AT LOW ω AND $> 90°$ AT HIGH ω
  2. MAGNITUDE OF $\dot{\theta}/\delta_{DS}$ FOLLOWS $K_{BS}/I_Y s$ AT HIGH ω BUT NOT AT LOW ω
  3. VAK-191B SHOULD EXHIBIT STABLE PITCH MOMENT IGE PROPORTIONAL TO θ
  4. DEAD TIME IN $\dot{\theta}$ FOLLOWING δ_{DS} MOTION DURING PITCH STEP
- **POSTULATED –**
  1. SECOND ORDER MODEL WITH θ AND $\dot{\theta}$ FEEDBACKS:

$$I_Y \ddot{\theta} = K_{BS}\,\delta_{BS} + M_{\dot{\theta}}\,\dot{\theta} + M_\theta\,\theta$$

$$\frac{\dot{\theta}}{\delta_{DS}} = \frac{-K_{BS}/M_\theta}{\frac{-I_Y}{M_\theta}s^2 + \frac{M_{\dot{\theta}}}{M_\theta}s + 1}$$

$M_\theta < 0$

$M_{\dot{\theta}} < 0$

  2. DEAD TIME AND/OR HIGHER FREQUENCY EFFECTS $-e^{-Ts} \rightarrow T > 0$
- **FITTED DATA –**

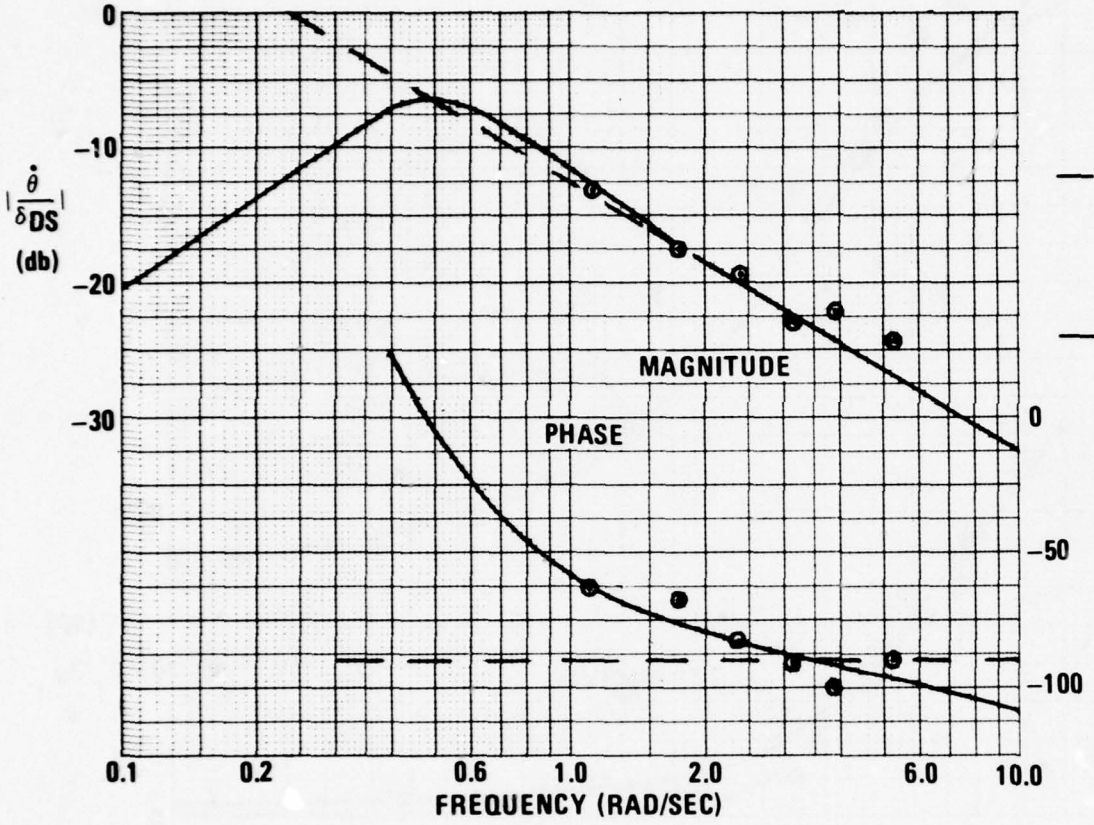
$$\frac{\dot{\theta}}{\delta_{DS}} = \frac{0.95e^{-0.04s}}{\left(\frac{s^2}{0.5^2} + \frac{2\,(0.5)}{0.5}s + 1\right)}$$

$M_\theta = -250$ FT-LB/DEG

$M_{\dot{\theta}} = -500$ FT-LB/DEG/SEC

$I_Y = 56{,}800$ SLUG FT^2

AIRCRAFT/PEDESTAL $\dot{\Theta}/\delta_{DS}$ FREQUENCY RESPONSE



⊙ ACTUAL DATA
PEDESTAL TEST
1.239

— — OGE PREDICTED RESPONSE

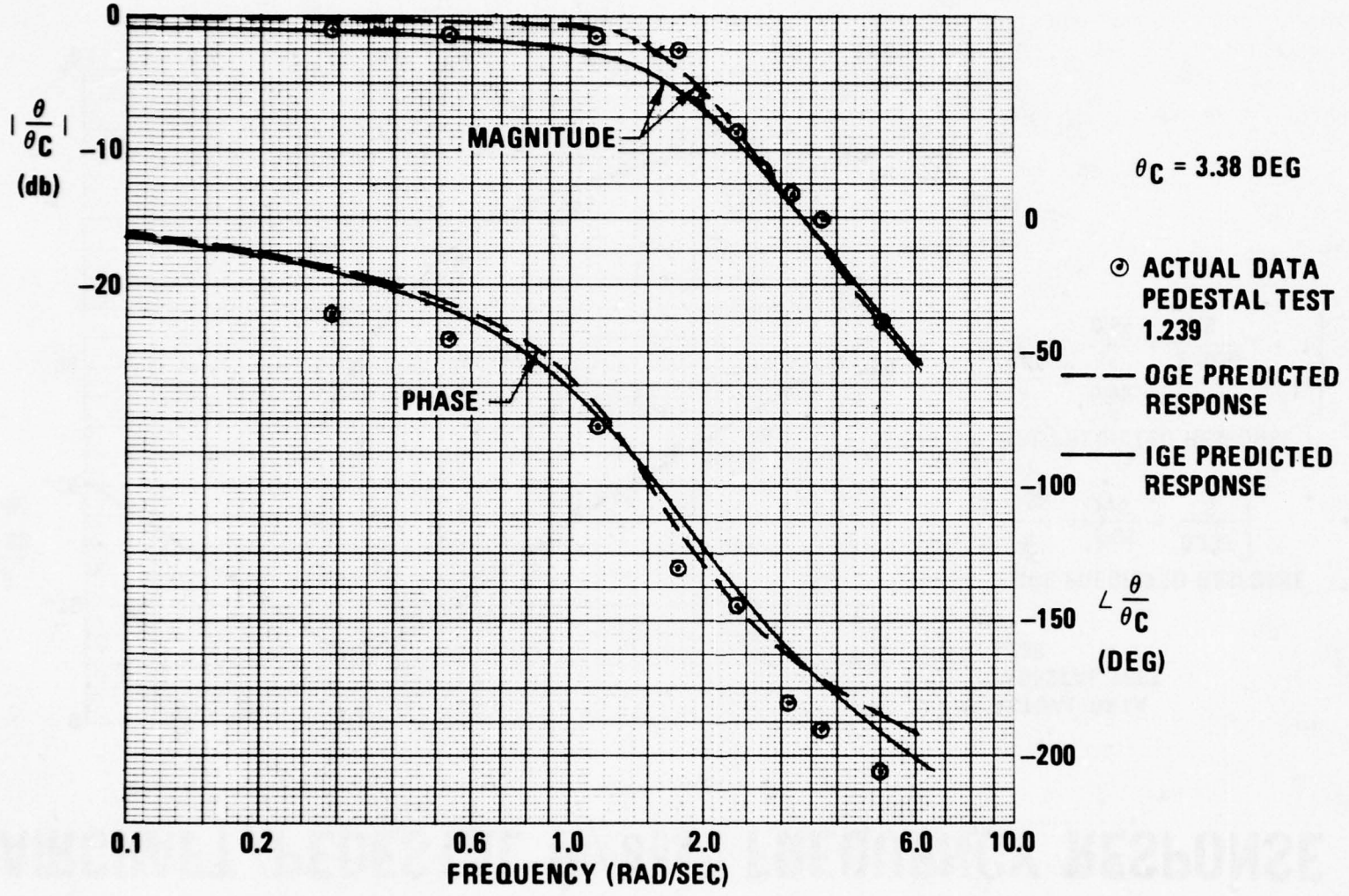
$$\left[\frac{\dot{\theta}}{\delta_{DS}} = \frac{K_{BS}}{I_Y S} = \frac{0.237}{S}\right]$$

——— IGE PREDICTED RESPONSE

$$\left[\frac{\dot{\theta}}{\delta_{DS}} = \frac{0.95s\, e^{-0.04s}}{\frac{s^2}{0.5^2} + \frac{2\,(0.5)}{0.5}\, s + 1}\right]$$

P7-393-19

CLOSED LOOP Θ/Θ_C FREQUENCY RESPONSE



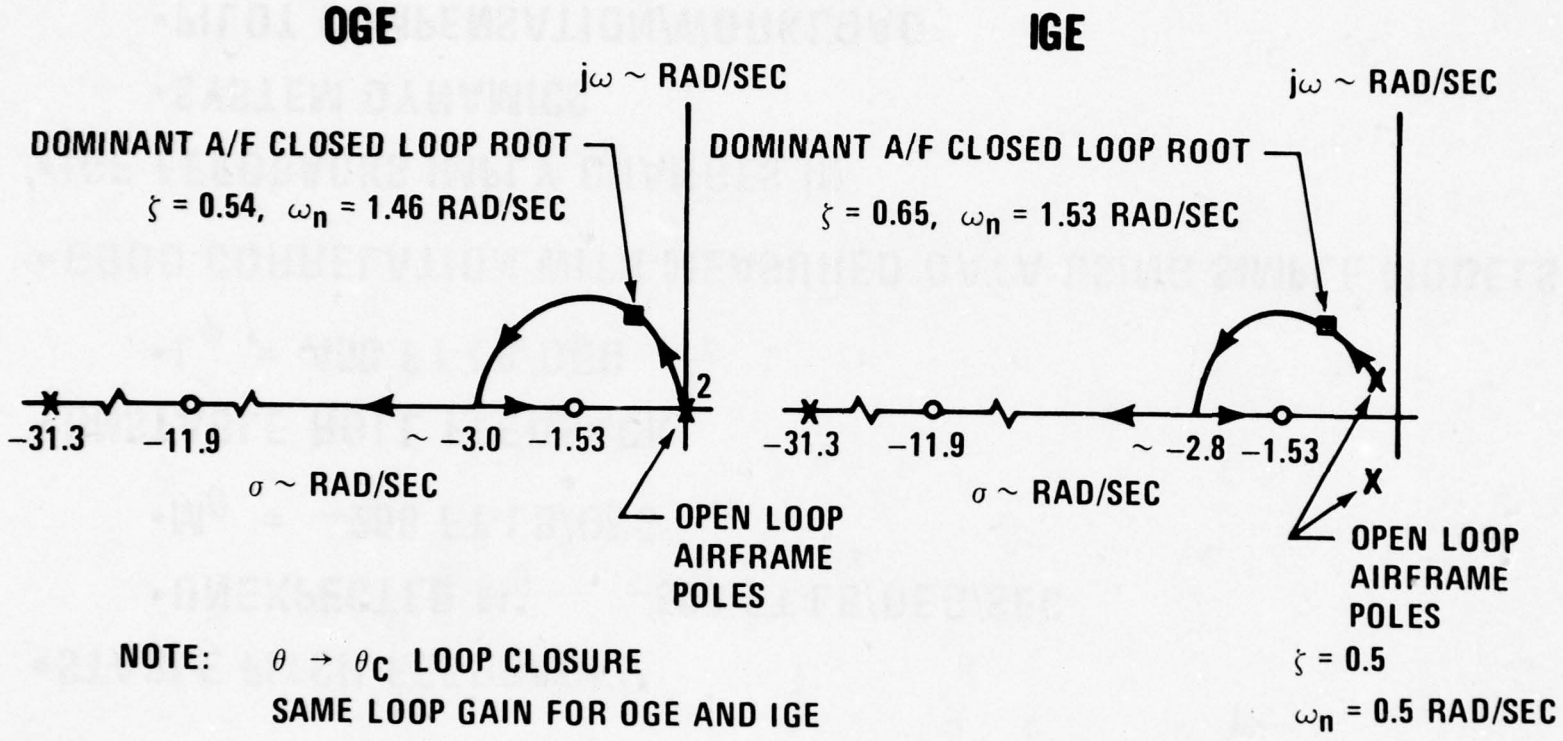
P7-383-14

VAK-191B FREQUENCY RESPONSE SUMMARY

- STABLE PITCH FEEDBACKS
  - UNEXPECTED $M_{\dot{\theta}}$ = –500 FT-LB/DEG/SEC
  - M_{θ} = –250 FT-LB/DEG
- UNSTABLE ROLL FEEDBACK
  - L_{ϕ} = 450 FT-LB/DEG
- GOOD CORRELATION WITH MEASURED DATA USING SIMPLE MODELS
- !GE FEEDBACKS IMPLY CHANGES IN
  - SYSTEM DYNAMICS
  - PILOT COMPENSATION/WORKLOAD
  - CONTROL POWER REQUIREMENTS
  - STATION-KEEPING STABILITY
- WHEN TRANSITIONING FROM OGE TO IGE OR VICE VERSA

DIFFERENCE IN VAK-191B CONTROLLED ELEMENT CHARACTERISTICS IN GROUND PROXIMITY

ROOT LOCUS COMPARISON OF PITCH ATTITUDE CONTROL

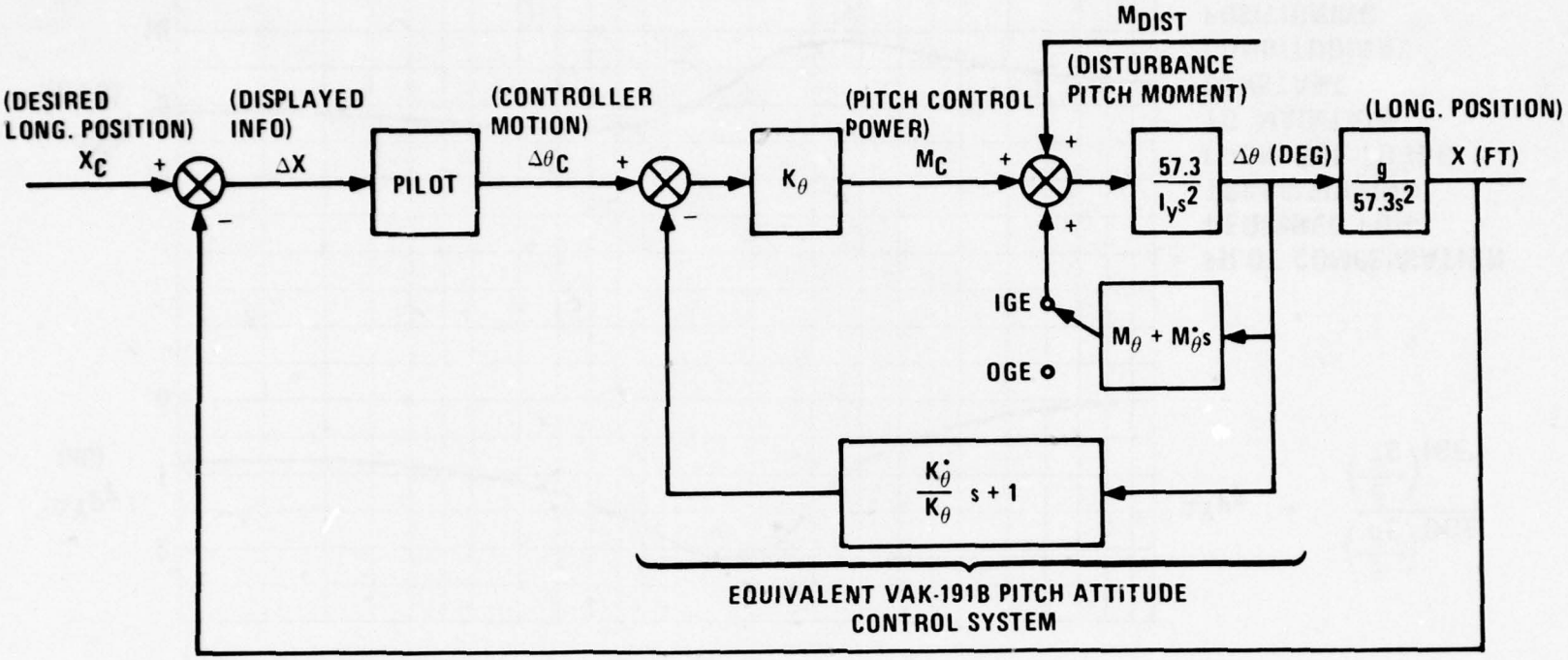


NOTE: $\theta \rightarrow \theta_C$ LOOP CLOSURE

SAME LOOP GAIN FOR OGE AND IGE

P7-393-13

MODEL OF VAK-191B LONGITUDINAL POSITION CONTROL IN HOVER



CONTROL SYSTEM GAINS

K_θ = 2131.6 FT-LB/DEG

$K_{\dot\theta}$ = 1576.8 FT-LB/DEG/SEC

IGE FEEDBACKS

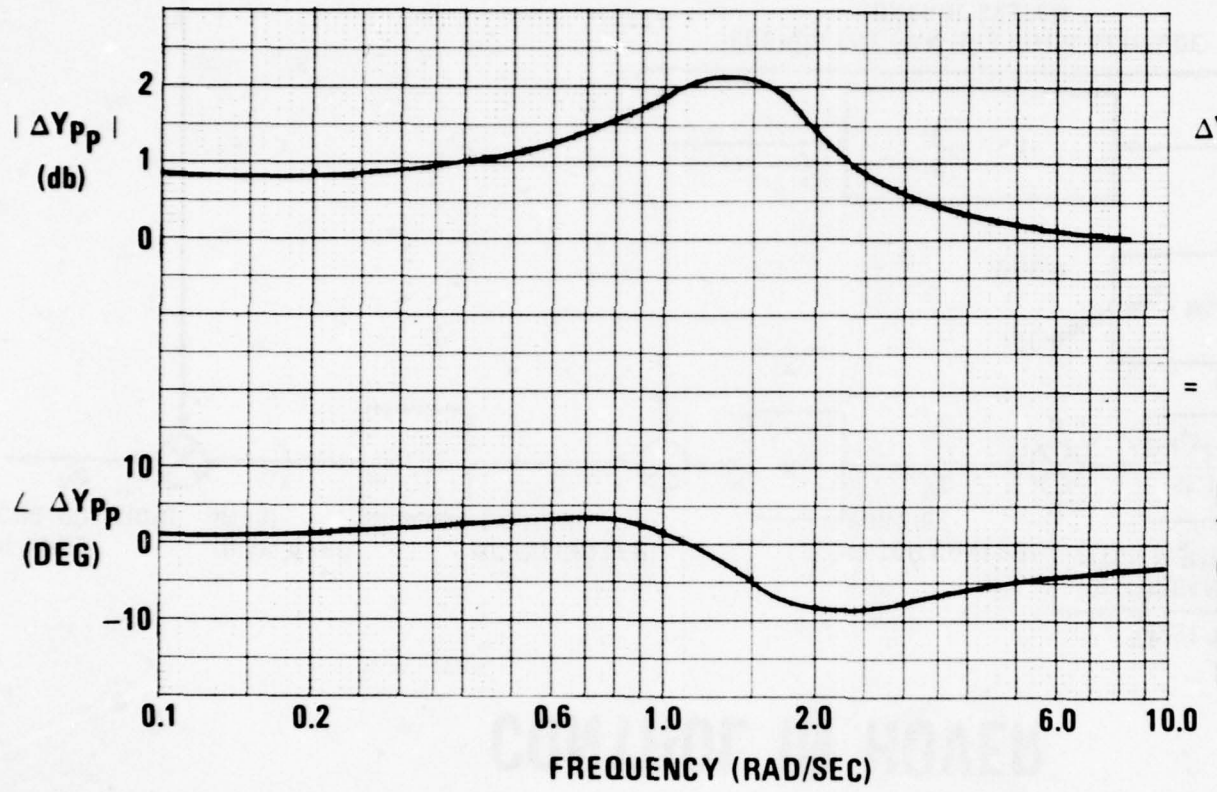
M_θ = −250 FT-LB/DEG

$M_{\dot\theta}$ = −500 FT-LB/DEG/SEC

I_y = 56,800 SLUG-FT^2

F7-383-10

PILOT COMPENSATION IN PITCH FOR OGE/IGE TRANSITION



$$\Delta Y_{PP} = \frac{\left(\frac{\theta}{\theta_C}\right)_{OGE}}{\left(\frac{\theta}{\theta_C}\right)_{IGE}}$$

= PILOT COMPENSATION REQUIRED FOR TRANSITIONING FROM OGE TO IGE TO MAINTAIN CONSTANT LONGITUDINAL POSITIONING PERFORMANCE

P7-393-21

PITCH CONTROL POWER EQUATIONS

C.P. FOR MANEUVERING

$$\frac{\theta}{M_C}(s) = \frac{0.001}{s^2 + 2\zeta\omega_n s + \omega_n^2} \text{(T.F.)}$$

$$M_C = \frac{M_{MAN}}{s} \text{ (INPUT)}$$

$$\theta(t) = M_{MAN}\mathcal{L}^{-1}\left[\frac{1}{s}\frac{\theta}{M_C}(s)\right]$$

$$M_{MAN} = \theta(1) \Big/ \left[\mathcal{L}^{-1}\left[\frac{1}{s}\frac{\theta}{M_C}(s)\right]\right]_{t=1}$$

$$\omega_n = \begin{cases} 1.46 & \text{OGE} \\ 1.53 & \text{IGE} \end{cases}$$

$$\zeta = \begin{cases} 0.54 & \text{OGE} \\ 0.66 & \text{IGE} \end{cases}$$

C.P. FOR CONTROLLING DISTURBANCES

$$\frac{M_C}{M_{DIST}}(s) = \frac{1.58\,(s + K_\theta / K_{\dot\theta})}{s^2 + 2\zeta\omega_n s + \omega_n^2} \text{ (T.F.)}$$

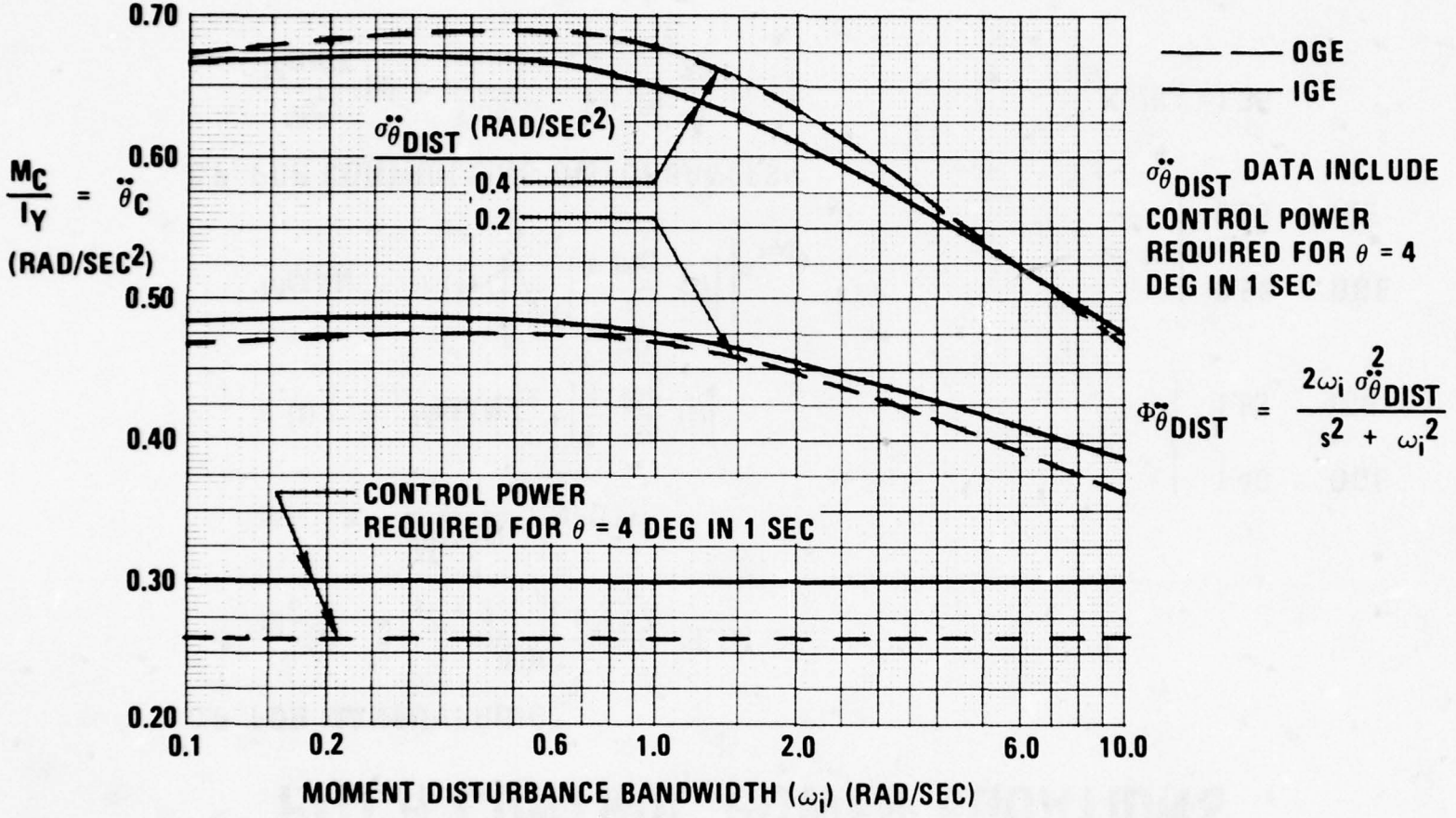
$K_\theta / K_{\dot\theta} = 1.35$

$$\Phi_{M_{DIST}}(s) = \frac{2\omega_i \sigma M_{DIST}^2}{s^2 + \omega_i^2} \text{ (INPUT)}$$

$$\overline{M_C^2} = \frac{1}{2\pi j}\int_{-j\infty}^{j\infty} \frac{M_C}{M_{DIST}}(s)\,\frac{M_C}{M_{DIST}}(-s)\,\Phi_{M_{DIST}}(s)\,ds = I_Y\,\overline{\ddot\theta_C^2}$$

P7-393-3

PITCH CONTROL POWER REQUIREMENTS



P7-393-20

DISCUSSION

Henry Kelley: In your discussion about the unstable rolling moment in ground effect as a function of bank angle, how did you measure that moment?

Fortenbaugh: Through the frequency response data. I had to assume that much to get it to match the data.

Kelley: From the pedestal data?

Fortenbaugh: Yes.

Kelley: How did you know that the source of the moment was, in fact, due to the jet efflux bouncing off the ground instead of from other sources?

Fortenbaugh: I don't care where it came from; it's there. It could have been sucked under the wing, and it could also have been the fountain effect. Possibly it's both. In any event, it was there and was something that we had to contend with in the airplane.

Kelley: Of the tests made in the past, it has been noted or suggested that this could be a possibility for developing destabilizing moments by V/STOL aircraft when in ground effect.

Fortenbaugh: Well, in this case, we were able to qualify the results from the frequency response data. Which kind of says that the pedestal tests were nice to have.

Anon: How far in ground (effect) was that measured?

Fortenbaugh: Bob, I don't remember the measurements.

Robert Traskos: It was about 0.7 H over V, which corresponded to a height of 11 feet above the ground.

Anon: And what kind of speed?

Fortenbaugh and Traskos: Zero.

Traskos: In fact, although we weren't able to show it on the slide, the pedestal was a static rig that was moveable in pitch, roll and yaw.

Ronald Hess: Bob, was there any data to indicate that the pilot was actually generating a second order lead?

Fortenbaugh: We'd need more data than we had.

Hess: In other words, they have hovered in ground effect.

Fortenbaugh: I didn't say that the pilot generated that. I said that to maintain the same performance in the outer loop, he would have had to generate that. I don't know whether he did or not. I don't think he did. Eric..

Erich Baitis: Did I understand you correctly to say that if you were going to stabilize in roll, it would require a 700 percent increase in control power?

Fortenbaugh: Well, for this airplane, if you want to do anything in ground effect other than land, I'd say that was a design consideration. We have to recognize that it's there. I think that we have to look into the wind-tunnel procedures to see how we're going to obtain it because our current wind-techniques cannot really predict it with respect to magnitude.

Kelley: Has the VAK-191B been hovering free? Unrestrained?

Traskos: Yes, it has hovered free, unrestrained in ground effect.

Kelley: How does the pilot control it?

Traskos: He essentially stayed out of the loop. The aircraft had a high gain, high authority attitude stabilization system and we found out that it was essentially a hands-off system. Anytime the pilot tried to control position in ground effect, he found himself PIO'ing the airplane with most of the action being about the lateral axis. Anytime he stopped with hands off, the airplane would drift, but without a bank angle problem.

Irving Ashkenas: Was lateral motion and ground effect a significant contributor to this rolling moment?

Traskos: It's primarily attitude. You compare the data of the two-poster type aircraft with the data of the wind-tunnel test and find there is some rolling up of the vortex in the motion, but primarily it's just attitude dependent. The ground effect is very sensitive to small changes in attitude and height. It's a combined height-attitude relationship.

Anon: Do they have wind-tunnel models of the VAK-191 that can be tested?

Fortenbaugh: Well, they've made an awful lot of them.

Anon: What I'd like to suggest is that you test the model in the wind tunnel in ground effect at different heights above the ground, and that at each height, you vary bank angle systematically and measure the rolling moment.

Fortenbaugh: I think that would probably be a good idea now that we have an indication of the magnitude of the effect. It might be something to go on, because this is still a very elusive problem in wind-tunnel testing. However, I don't know whether we can trust all the data that we obtain from wind-tunnel tests.

John Williams: Some tests of this nature have been conducted with the Harrier in the U.K. The difficulty has been in simulating the jet exhaust flow, and that truly presents great problems. The effect was certainly demonstrated and some figures were deduced from the tests showing the variability of critical bank angle with height above the ground.

Anon: In the wind-tunnel tests, wouldn't you lose the dynamics that are experienced in flight?

Fortenbaugh: Well, you could measure this, since this is just the slope of the rolling moment vs. bank angle curve. Correct me if I'm wrong, but the VAK-191 wind-tunnel tests missed by 50 percent on the propulsion induced effects relative to the pitch axis. I don't know how they did in roll. Bob, you were more familiar with the pedestal rig than I was.

Traskos: The pedestal rig that these full scale tests were done on was essentially a single post arrangement attached to the airplane at approximately the center of gravity. The pitch axis was free while the roll axis was an offset parallelogram; however, we were rotating the airplane around the centerline of the airplane. Yaw was a swivel about the basic post. As I've said before, the bottom of the aircraft was about 12 feet above the ground.

Anon: What was the magnitude of the bank angle?

Fortenbaugh: I was just going to comment on that. I might mention that the magnitude of the bank angle in the frequency response data which was shown was four degrees. They tried eight degrees, but as you noticed, there was a very high gain at low frequencies. Consequently at the low frequencies, the airplane just rolled over to the side and remained there when they tried to drive it with an eight degree magnitude. If you make a calculation with the math model, it turns out that you're exceeding the roll power of the airplane.

Traskos: I think that probably what added to the credibility of this calculation was the fact that the only way you could get the airplane upright and wings level was to reduce power. Tests were done at a flight RPM on all engines. When it flopped over to about 15 degree bank angle, we could not bring it back up with full control. The only way we could get it back up was to pull the power back. Then the airplane became upright pretty much by itself.

Fortenbaugh: You might note that the middle fountain here (pointing to a slide) was probably broken up by the presence of the pedestal. There were three fountains on the aircraft, so possibly you didn't even have the full effect of the jet efflux. That was only a small part of the effect.

Jack Franklin: Bob, did you have any indication of what the influence of winds, particularly cross winds, might be on the ground effect?

Fortenbaugh: I don't know of any data. Bob may know of some.

Traskos: As for the comparison, Jack, do you mean a comparison between bank angle and cross wind? We weren't allowed to go that far in a cross wind so as to really determine the influence. It was quite large, but we could not make a comparison to show a value such as five knots of wind per degree of bank angle.

Franklin: What the last question leads to is that the airplane, under its present configuration, cannot be flown in a crosswind because one must balance the side force with the bank angle.

Fortenbaugh: At least, not very much crosswind.

Franklin: That would certainly be part of a normal VTOL plan.

Traskos: True. We were limited to five knots of crosswind during vertical takeoffs, to my recollection.

LTCOL J.E. Iles: May I make a comment? The practical result of all these big numbers that you're seeing here is that the pilot, in a jet-lift aircraft like this one, doesn't maneuver the airplane in ground effect if he's smart. And the second thing to note is that his gain value around roll attitude is very high. If he has to hover in a crosswind for any reason, he can't be combining that adequately with any relaxation of his roll attitude control. There has to be high gain on it. I think that Mike Deitchman may be able to answer a question about pilot lead. I don't know the data since I haven't had a chance to look at it yet.

Fortenbaugh: Mike, do you want to make a comment on that point?

Mike Deitchman: Not really.

Fortenbaugh: O.K.

Iles: To summarize, the pilot gain has to be at a very high value about the roll axis. You just don't maneuver in ground effect. You set yourself up out of ground effect, and then come through as quickly as possible.

SESSION III

PILOT CENTERED REQUIREMENTS IN CONTROL/DISPLAY DESIGN

Dr. Ronald A. Hess

NASA Ames Research Center

SLIDE 1

The V/STOL control/display problem could be solved, by definition, if this 3-dimensional surface could be analytically quantified for any vehicle and task.

SLIDE 2

One approach to quantifying this surface is to utilize analytical models of the human pilot. One such model which has seen increasing acceptance in recent years is the so-called Optimal Control Model of the human pilot.

SLIDE 3

Here one sees a block diagram of the closed-loop pilot/vehicle system incorporating the optimal control model of the human pilot.

SLIDE 4

A method has been developed for predicting pilot opinion ratings for particular vehicles and tasks using the optimal control pilot model. The method is documented in references 1-2. The hypothesis behind the rating scheme is shown here.

SLIDE 5

This slide shows the $R(J)_s$ which has been developed for the Cooper-Harper scale. The actual pilot opinion ratings for 18 vehicle configurations and tasks are plotted vs the value of the index of performance obtained from modeling the pilot in these 18 cases.

SLIDE 6

The design of an acceptable flight director is an important element in a display design procedure. Here we see the outline of a flight director design procedure based upon the optimal control pilot model discussed in greater detail in reference 3.

SLIDE 7

A flight director design example, taken from references 4 and 5, is indicated on this slide. It involves the longitudinal control of a helicopter in hover.

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SLIDE 8

The display used by the pilot in the simulation study accompanying the director design effort is shown here.

SLIDE 9

The comparison of pilot model and pilot-in-the-loop simulation RMS performance scores are shown here for a preliminary flight director design. A significant improvement in actual pilot opinion rating was noted with the director also.

SLIDE 10

Reference 4 documents a straightforward, nearly algorithmic analytical display desing procedure outlined in the flowchart of this slide. The procedure again utilizes the optimal control model of the human pilot.

SLIDE 11

The display design-oriented pilot modeling results are shown here. These can lead somewhat naturally to display information and format requirements for specific vehicles and tasks.

SLIDE 12

A display design example from references 4 and 5 is outlined here. The longitudinal and lateral control of a helicopter in a -6^{0} constant groundspeed-command landing approach task is considered.

SLIDE 13

As part of the display design, an analytical investigation of the effect of pilot allocation of attention between longitudinal and lateral control is shown here for 3 vehicle/display configurations. The first entails an unaugmented vehicle with a baseline (status information only) display. The second includes a rudimentary stability augmentation system utilizing feedback of groundspeed errors to longitudinal cyclic in parallel to the pilot's control input. Finally, the third configuration includes a "3-cue" flight director designed according to the philisophy outlined in slide 6.

SLIDE 14

This slide indicates the relative approximate power in each of the four controls available to the pilot which are associated with the displayed variables shown for the baseline case. Also included are the predicted fractions of attention on each display variable (and its perceived derivative) for the longituidnal and lateral modes.

SLIDE 15

Here we see the model generated information similar to that for slide 15 except that the simple stability augmentation system has been included.

SLIDE 16

A proposed display format is shown here which has been generated via the general guidelines offered in reference 4.

SLIDE 17

The results of the display design example are shown in quantitative fashion on the surface of slide 1.

REFERENCES

1. Hess, R. A.; A Method for Generating Numerical Pilot Opinion Ratings Using the Optimal Pilot Model, NASA TM X-73,101, February 1976.

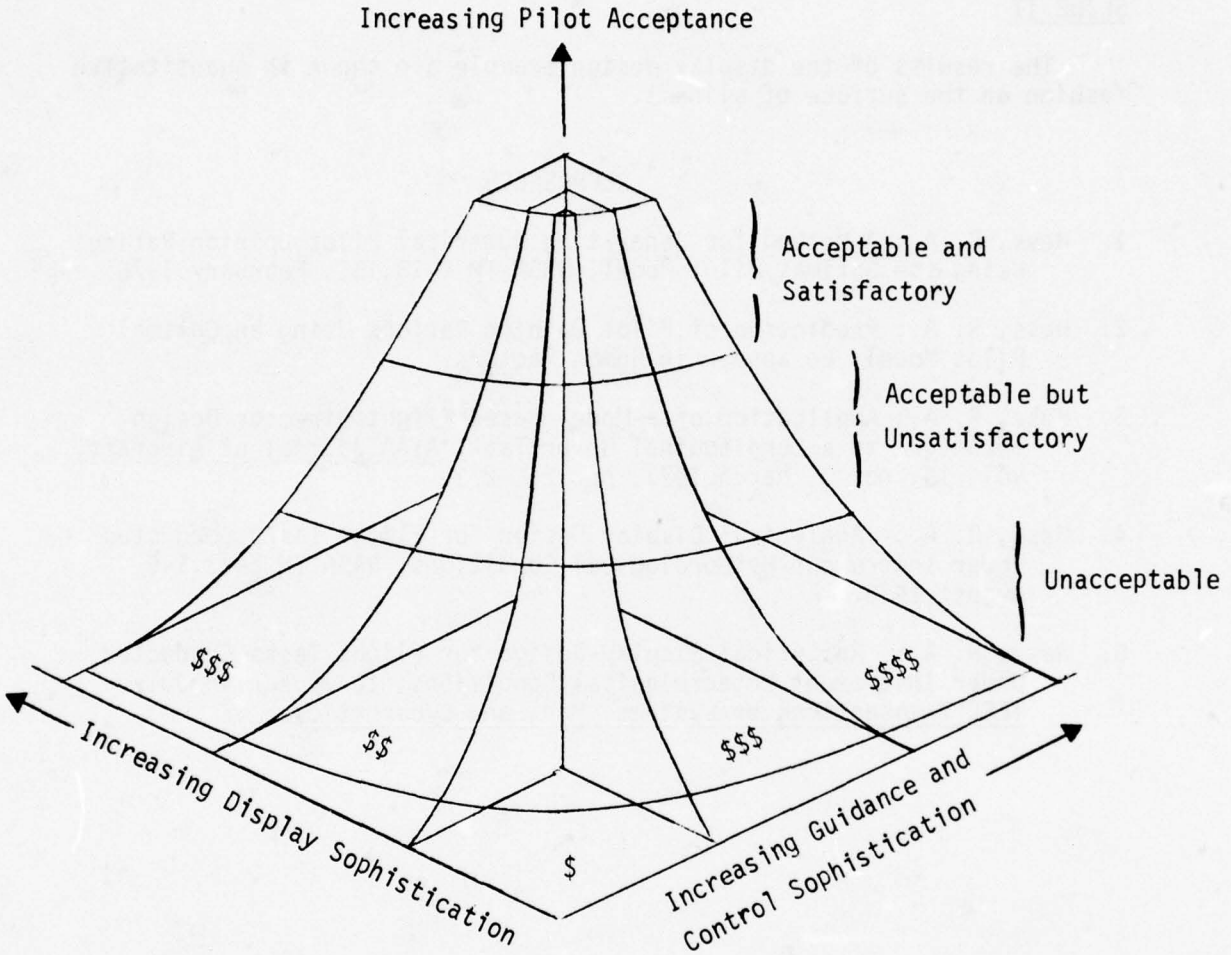
2. Hess, R. A.; Prediction of Pilot Opinion Ratings Using an Optimal Pilot Model, to appear in Human Factors.

3. Hess, R. A.; Application of a Model-Based Flight Director Design Technique to a Longitudinal Hover Task, AIAA Journal of Aircraft, vol. 14, no. 3, March 1977, pp. 265-271.

4. Hess, R. A.; Analytical Display Design for Flight Tasks Conducted Under Instrument Meteorological Conditions, NASA TM X-73,146, August 1976.

5. Hess, R. A.; Analytical Display Design for Flight Tasks Conducted Under Instrument Meteorological Conditions, to appear in July IEEE Transactions on Systems, Man, and Cybernetics.

SLIDE (1)



$ - relative cost

THE CONTROL/DISPLAY PROBLEM

SLIDE (2)

MODERN CONTROL APPROACH TO HUMAN PILOT MODELING

OBJECTIVES

DEVELOP AND APPLY ANALYSIS PROCEDURES FOR MANUALLY CONTROLLED SYSTEMS

APPROACH

COMBINE HUMAN RESPONSE THEORY WITH MODERN CONTROL AND ESTIMATION THEORY

ASSUMPTION

EXPERIENCED HUMAN BEHAVES OPTIMALLY SUBJECT TO HIS INHERENT LIMITATIONS

APPLICATIONS TO MANNED VEHICLE SYSTEMS

BASIC MANUAL CONTROL TASKS

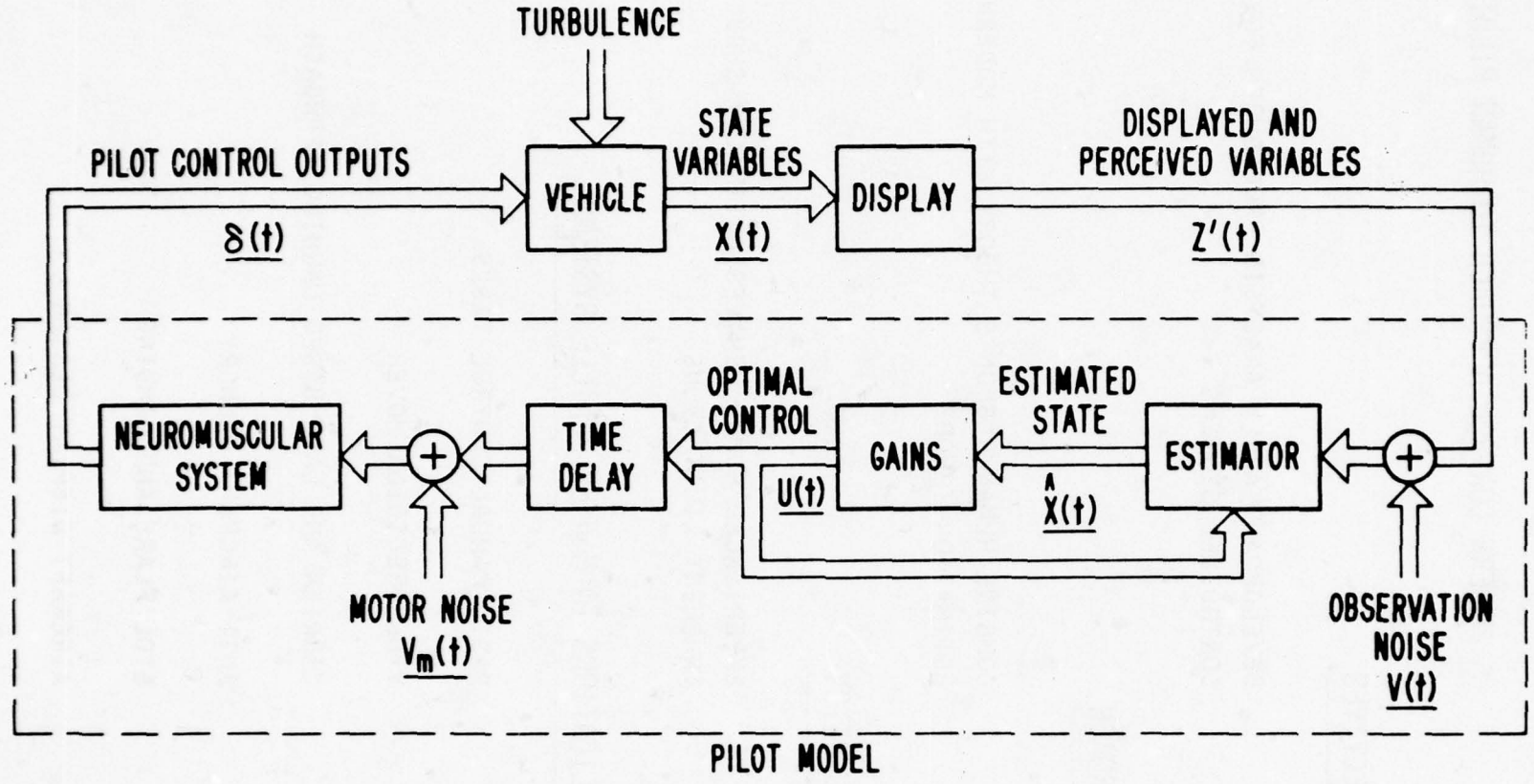
VTOL PRECISION HOVER

CARRIER AND LAND-BASED LANDING APPROACH

ANTI-AIRCRAFT GUNNERY

STOL FLARE AND LANDING

AIRCRAFT DISPLAY DESIGN


TURBULENCE
PILOT CONTROL OUTPUTS
δ(t)
VEHICLE
STATE VARIABLES
X(t)
DISPLAY
DISPLAYED AND PERCEIVED VARIABLES
Z'(t)
NEUROMUSCULAR SYSTEM
TIME DELAY
OPTIMAL CONTROL
U(t)
GAINS
ESTIMATED STATE
X̂(t)
ESTIMATOR
MOTOR NOISE
Vm(t)
OBSERVATION NOISE
V(t)
PILOT MODEL

SLIDE (3)

SLIDE ④

PREDICTING PILOT OPINION RATINGS

HYPOTHESIS

GIVEN THE QUADRATIC INDEX OF PERFORMANCE WHICH DEFINES THE OPTIMAL CONTROL PILOT MODEL

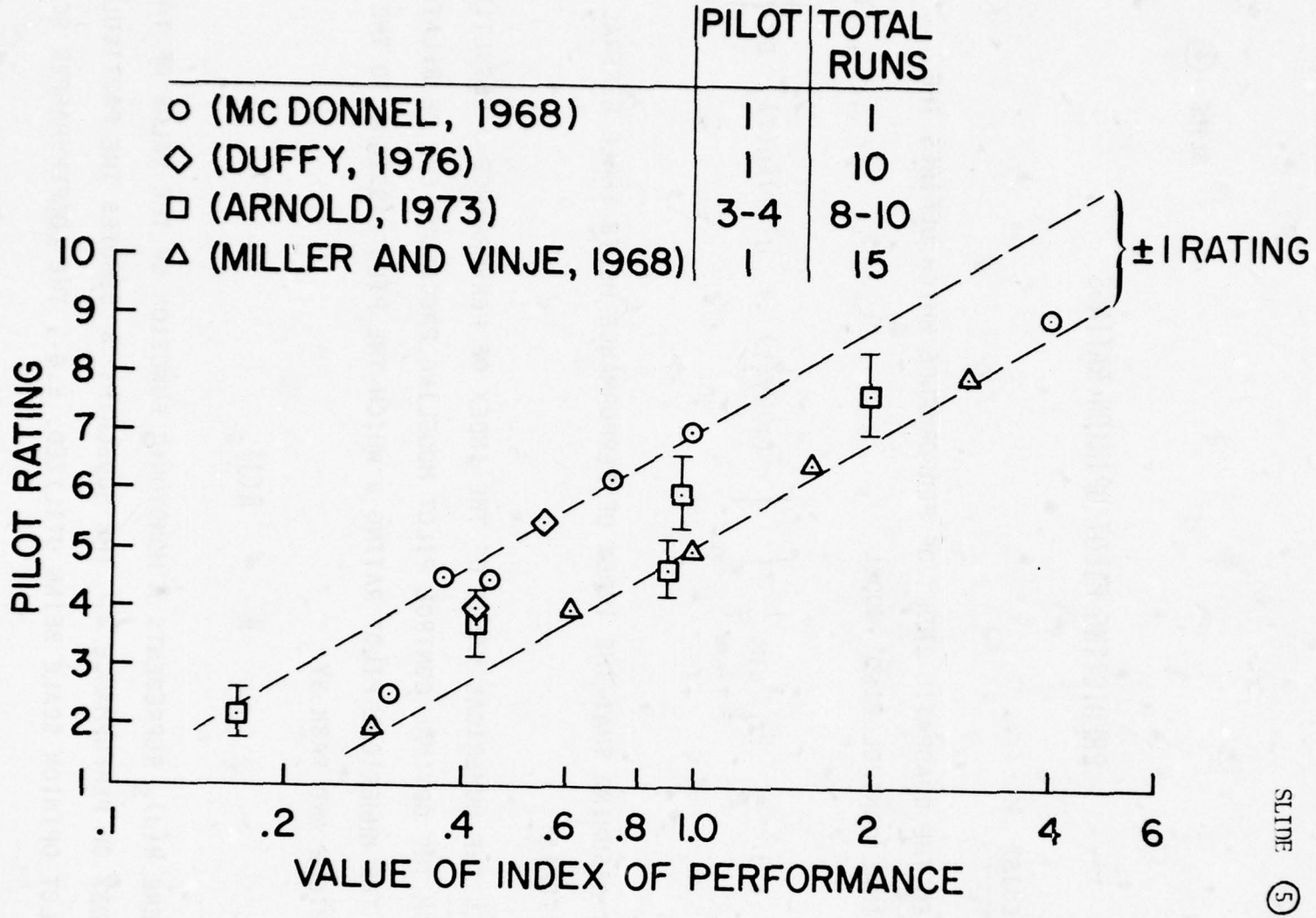
$$J = E\left\{ \lim_{T\to\infty} \frac{1}{T} \int_0^T \left[Y^T(T)QY(T) + U^T(T)RU(T) \right] DT \right\}$$

AND ASSUMING THAT THE INDEX OF PERFORMANCE MEETS THREE GENERAL CRITERIA,

THEN THE NUMERICAL VALUE OF THE INDEX OF PERFORMANCE J RESULTING FROM THE OPTIMAL CONTROL PILOT MODELING PROCEDURE CAN BE RELATED TO THE NUMERICAL PILOT RATING R WHICH THE PILOT ASSIGNS TO THE VEHICLE AND TASK BY

$$R = R(J)_S$$

WHERE $R(J)_S$ REPRESENTS A MONOTONIC FUNCTION OF THE VALUE OF THE INDEX OF PERFORMANCE J. THE SUBSCRIPT S DENOTES THE PARTICULAR PILOT OPINION SCALE BEING UTILIZED, E.G., THE COOPER-HARPER SCALE.


PILOT
TOTAL RUNS
(Mc DONNEL, 1968) 1 1
(DUFFY, 1976) 1 10
(ARNOLD, 1973) 3-4 8-10
(MILLER AND VINJE, 1968) 1 15
±1 RATING
PILOT RATING
10
9
8
7
6
5
4
3
2
1
.1
.2
.4
.6
.8
1.0
2
4
6
VALUE OF INDEX OF PERFORMANCE

SLIDE (5)

SLIDE ⑥

FLIGHT DIRECTOR DESIGN TECHNIQUE

(A) GIVEN THE VEHICLE/TURBULENCE MODEL AND THE BASELINE DISPLAY, GENERATE A PILOT MODEL. THE PERTINENT RESULTS OF THIS MODELING PROCEDURE WILL BE:

(1) PREDICTED PILOT TRANSFER FUNCTIONS $H_{IJ}(s)$ BETWEEN EACH PILOT CONTROL OUTPUT $U_I(T)$ AND EACH OBSERVED VARIABLE $Z'_J(T)$

(2) THE AVERAGE POWER P_{IJ} IN EACH PILOT OUTPUT $U_I(T)$ WHICH IS ASSOCIATED WITH EACH OBSERVED VARIABLE $Z'_J(T)$.

(B) ORDER EACH PILOT TRANSFER FUNCTION $H_{IJ}(s)$ CALCULATED IN (A1) ACCORDING TO THE MAGNITUDE OF THE CORRESPONDING AVERAGE POWER P_{IJ} IN (A2). BASED UPON THIS ORDER, CHOOSE N_K ESSENTIAL OBSERVED VARIABLES FOR EACH PILOT CONTROL.

(C) FORMULATE THE FLIGHT DIRECTOR LAWS (ONE FOR EACH CONTROL IF WORKLOAD ALLOWS) AS FOLLOWS:

$$D_I(s) = \sum_{J=1}^{N_K} H_{IJ}(s)\, Z'_J(s)$$

(D) REFINE THE PILOT MODEL USING SIMULATION RESULTS AND REPEAT STEPS (A) THROUGH (C) AGAIN.

SLIDE (7)

FLIGHT DIRECTOR DESIGN EXAMPLE

VEHICLE

UH-1H HELICOPTER

TASK

LONGITUDINAL HOVER AT SPECIFIED HEIGHT OVER A LANDING PAD 15.2 M (50 FT) ON A SIDE

TURBULENCE

LONGITUDINAL WITH INTENSITY OF 1.52 M/SEC (5 FT/SEC)

CONTROLS AVAILABLE TO PILOT

LONGITUDINAL CYCLIC PITCH AND COLLECTIVE PITCH

SLIDE (8)

SPLAY GAINS:

PITCH ATTITUDE .127 cm/deg

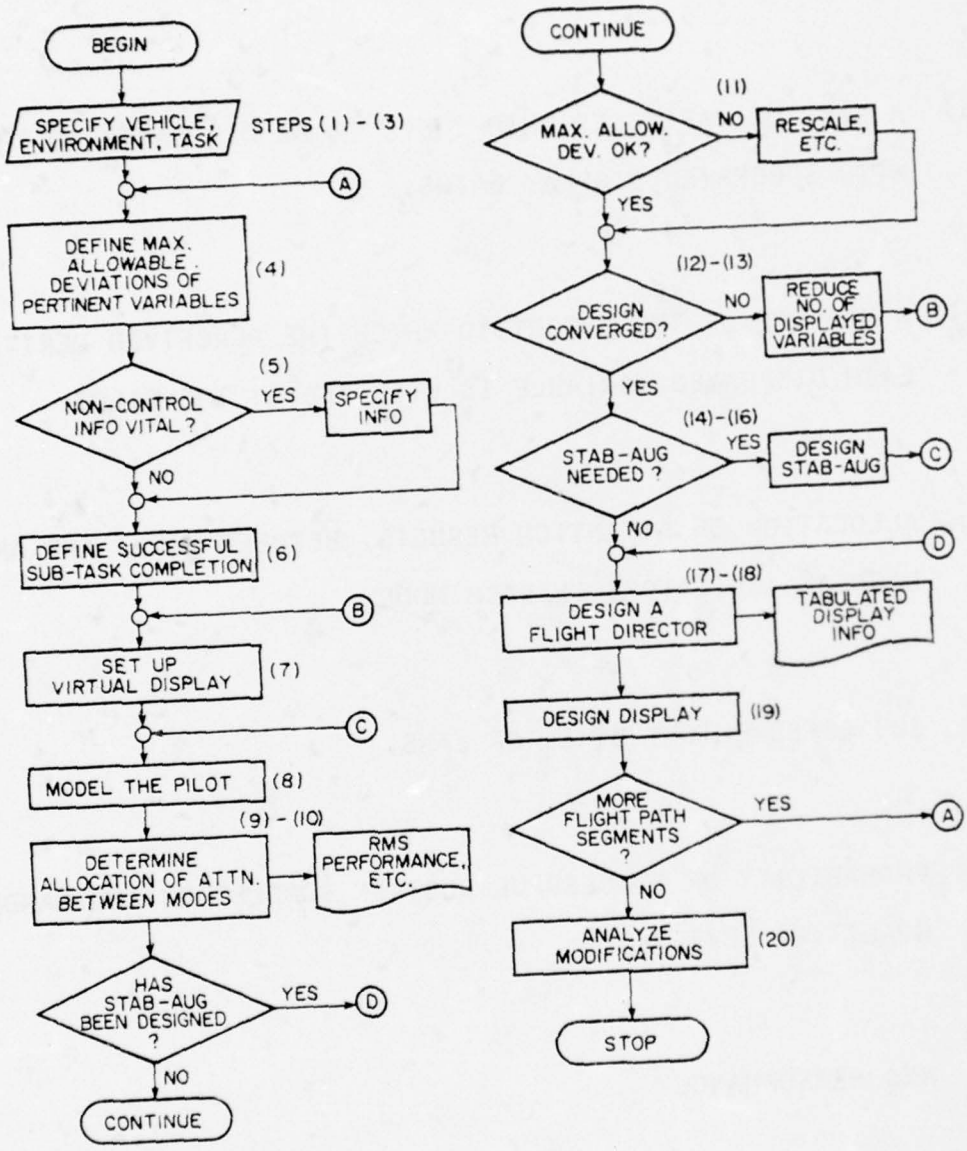
GLIDESLOPE DEVIATION .167 cm/m

LONGITUDINAL DISPLACEMENT .333 cm/m
FROM LANDING PAD

SLIDE (9)

$\sqrt{\overline{x^2(t)}}$ (m)
$\sqrt{\overline{\dot{x}^2(t)}}$ (m/sec)
$\sqrt{\overline{\theta^2(t)}}$ (rad)
$\sqrt{\overline{\delta_B^2(t)}}$ (cm)
$\sqrt{\overline{\dot{\theta}^2(t)}}$ (rad/sec)
$\sqrt{\overline{h^2(t)}}$ (m)
$\sqrt{\overline{\dot{h}^2(t)}}$ (m/sec)
$\sqrt{\overline{\delta_c^2(t)}}$ (cm)
S = std dev
MEAN ± 2·S
BASELINE DIRECTOR
● MODEL
○ EXPERIMENT

SLIDE (10)


BEGIN
SPECIFY VEHICLE, ENVIRONMENT, TASK
STEPS (1) - (3)
A
DEFINE MAX. ALLOWABLE DEVIATIONS OF PERTINENT VARIABLES
(4)
NON-CONTROL INFO VITAL ?
(5)
YES
SPECIFY INFO
NO
DEFINE SUCCESSFUL SUB-TASK COMPLETION
(6)
B
SET UP VIRTUAL DISPLAY
(7)
C
MODEL THE PILOT
(8)
DETERMINE ALLOCATION OF ATTN. BETWEEN MODES
(9) - (10)
RMS PERFORMANCE, ETC.
HAS STAB-AUG BEEN DESIGNED ?
YES
D
NO
CONTINUE
CONTINUE
MAX. ALLOW. DEV. OK?
(11)
NO
RESCALE, ETC.
YES
DESIGN CONVERGED?
(12) - (13)
NO
REDUCE NO. OF DISPLAYED VARIABLES
B
YES
STAB-AUG NEEDED ?
(14) - (16)
YES
DESIGN STAB-AUG
C
NO
D
DESIGN A FLIGHT DIRECTOR
(17) - (18)
TABULATED DISPLAY INFO
DESIGN DISPLAY
(19)
MORE FLIGHT PATH SEGMENTS ?
YES
A
NO
ANALYZE MODIFICATIONS
(20)
STOP

SLIDE (11)

DESIGN-ORIENTED PILOT MODELING RESULTS

(A) A LIST OF VARIABLES WHICH NEED TO BE DISPLAYED TO THE PILOT WITH SUGGESTED DISPLAY GAINS,

(B) A MEASURE OF THE EXTENT TO WHICH THE PERCEIVED DERIVATIVE OF EACH DISPLAYED VARIABLE IS UTILIZED BY THE PILOT,

(C) ALLOCATION OF ATTENTION RESULTS, BETWEEN MODES AND AMONG DISPLAY INDICATORS IN EACH MODE,

(D) SUGGESTED FLIGHT DIRECTOR LAWS,

(E) PROBABILITY OF SUCCESSFUL SUBTASK COMPLETION AND HANDLING QUALITIES LEVELS,

(F) RMS PERFORMANCE

DISPLAY DESIGN EXAMPLE

SLIDE (12)

VEHICLE

UH-1H HELICOPTER

TASK

CONSTANT GROUNDSPEED (20.6 M/SEC (40 KNOTS)) LANDING APPROACH ON -6^{o} GLIDESLOPE WITH LONGITUDINAL AND LATERAL MOTION

TURBULENCE

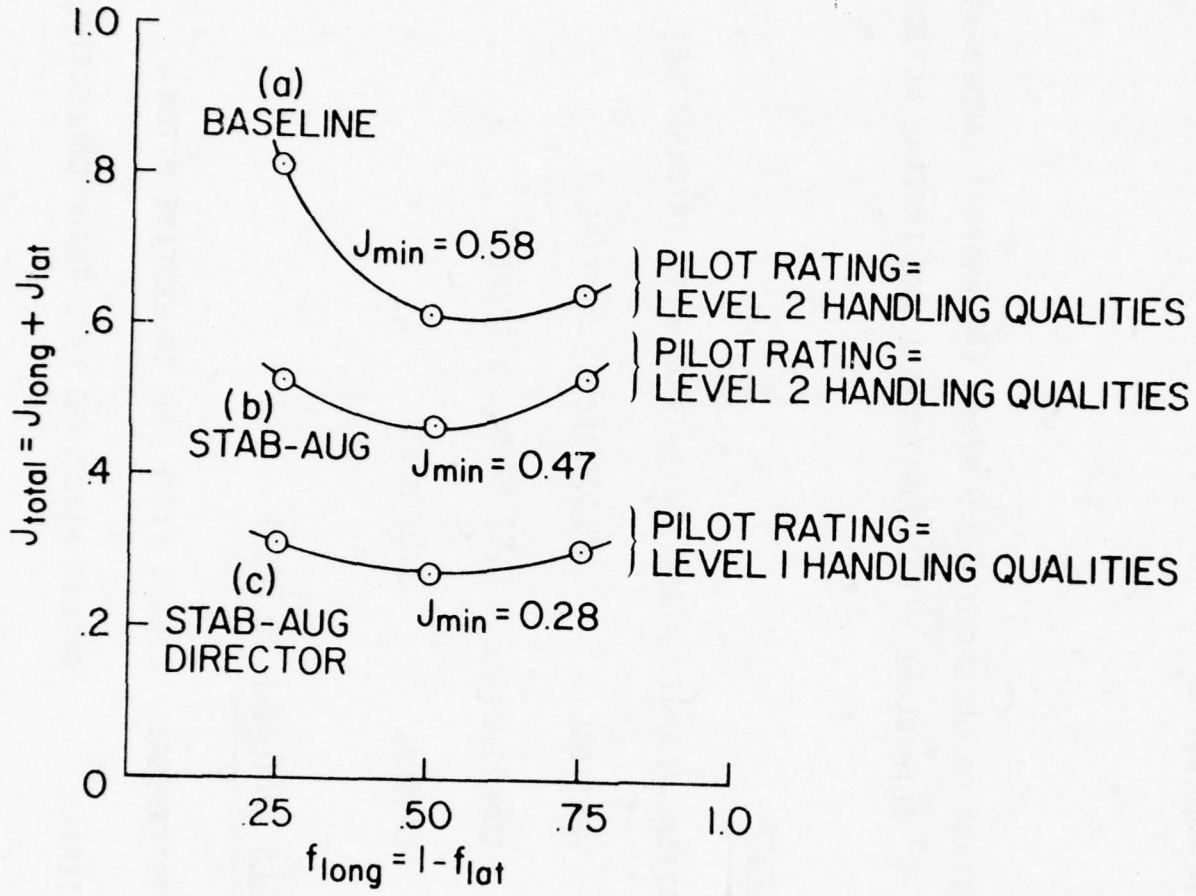
VERTICAL, LONGITUDINAL AND LATERAL WITH INTENSITIES:

VERTICAL	.762 M/SEC (2.5 FT/SEC)
LONGITUDINAL	1.52 M/SEC (5 FT/SEC)
LATERAL	1.52 M/SEC

CONTROLS AVAILABLE TO PILOT

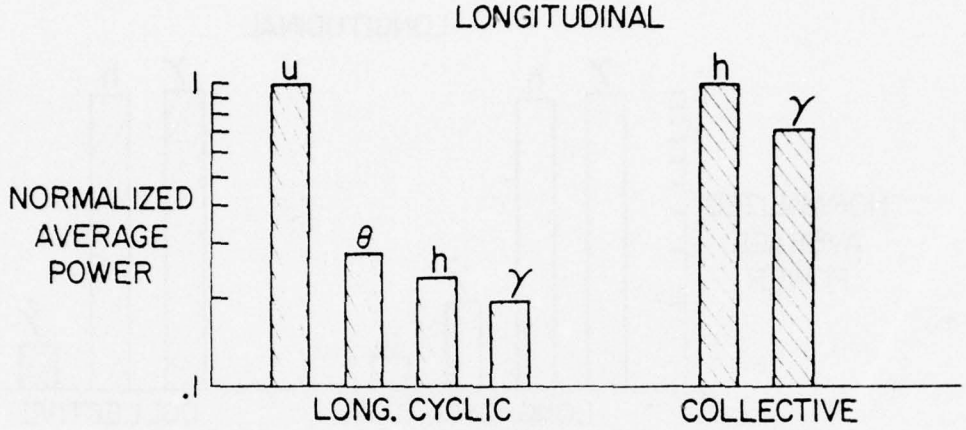
LONGITUDINAL: CYCLIC PITCH AND COLLECTIVE PITCH

LATERAL: CYCLIC PITCH AND TAIL ROTOR COLLECTIVE PITCH

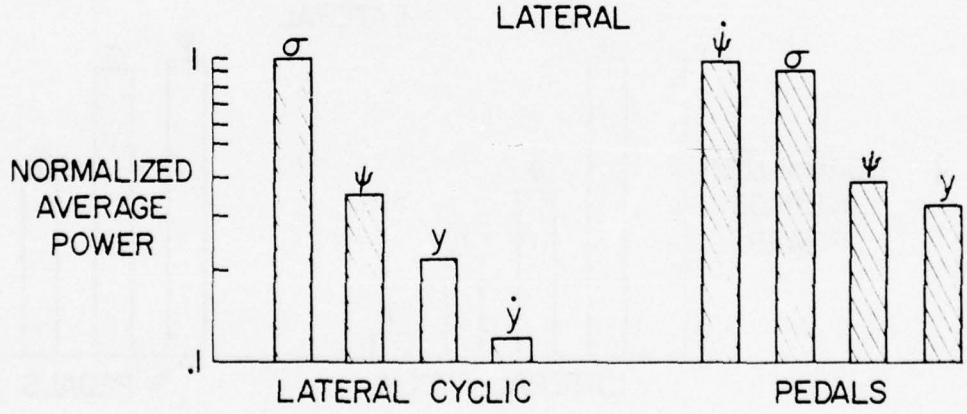

1.0
.8
.6
.4
.2
0
$J_{total} = J_{long} + J_{lat}$
(a)
BASELINE
$J_{min} = 0.58$
PILOT RATING =
LEVEL 2 HANDLING QUALITIES
(b)
STAB-AUG
$J_{min} = 0.47$
PILOT RATING =
LEVEL 2 HANDLING QUALITIES
(c)
STAB-AUG
DIRECTOR
$J_{min} = 0.28$
PILOT RATING =
LEVEL 1 HANDLING QUALITIES
.25
.50
.75
1.0
$f_{long} = 1 - f_{lat}$

SLIDE (13)

SLIDE (14)

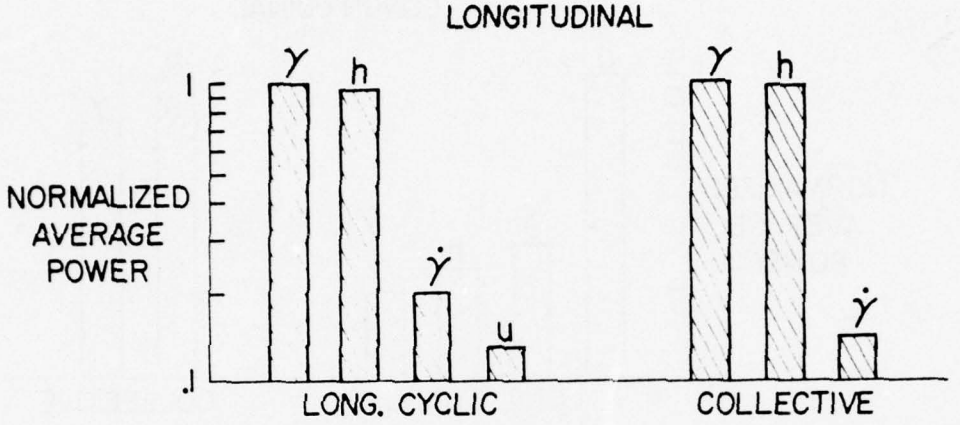


FRACTIONS OF ATTENTION: $f_{h,\dot{h}} = 0.35$ $f_{u,\dot{u}} = 0.22$ $f_{\gamma,\dot{\gamma}} = .29$ $f_{\theta,\dot{\theta}} = .14$

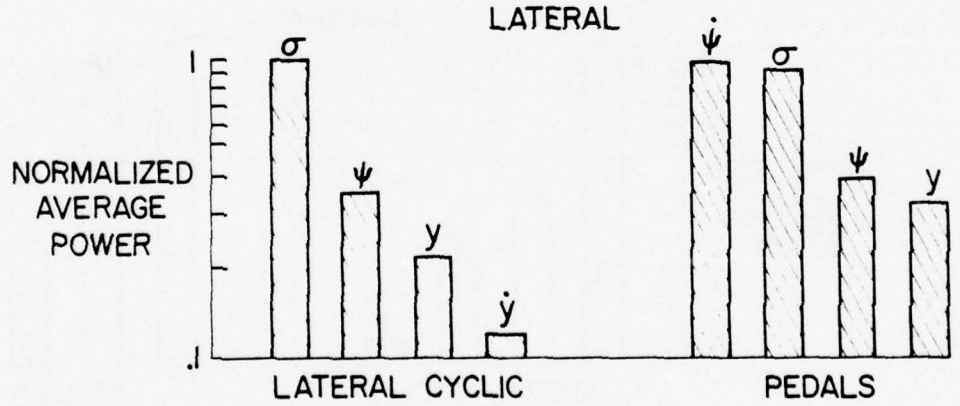


FRACTIONS OF ATTENTION: $f_{\sigma,\dot{\sigma}} = 0.43$ $f_{\psi,\dot{\psi}} = 0.19$ $f_{y,\dot{y}} = .26$ $f_{\phi,\dot{\phi}} = .12$

SLIDE (15)

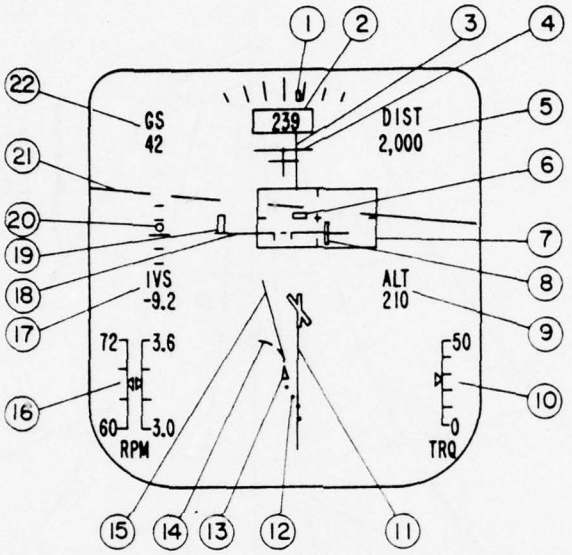


FRACTIONS OF ATTENTION: $f_{h,\dot{h}} = 0.50$ $f_{u,\dot{u}} = 0.05$ $f_{\gamma,\dot{\gamma}} = .42$ $f_{\theta,\dot{\theta}} = .03$



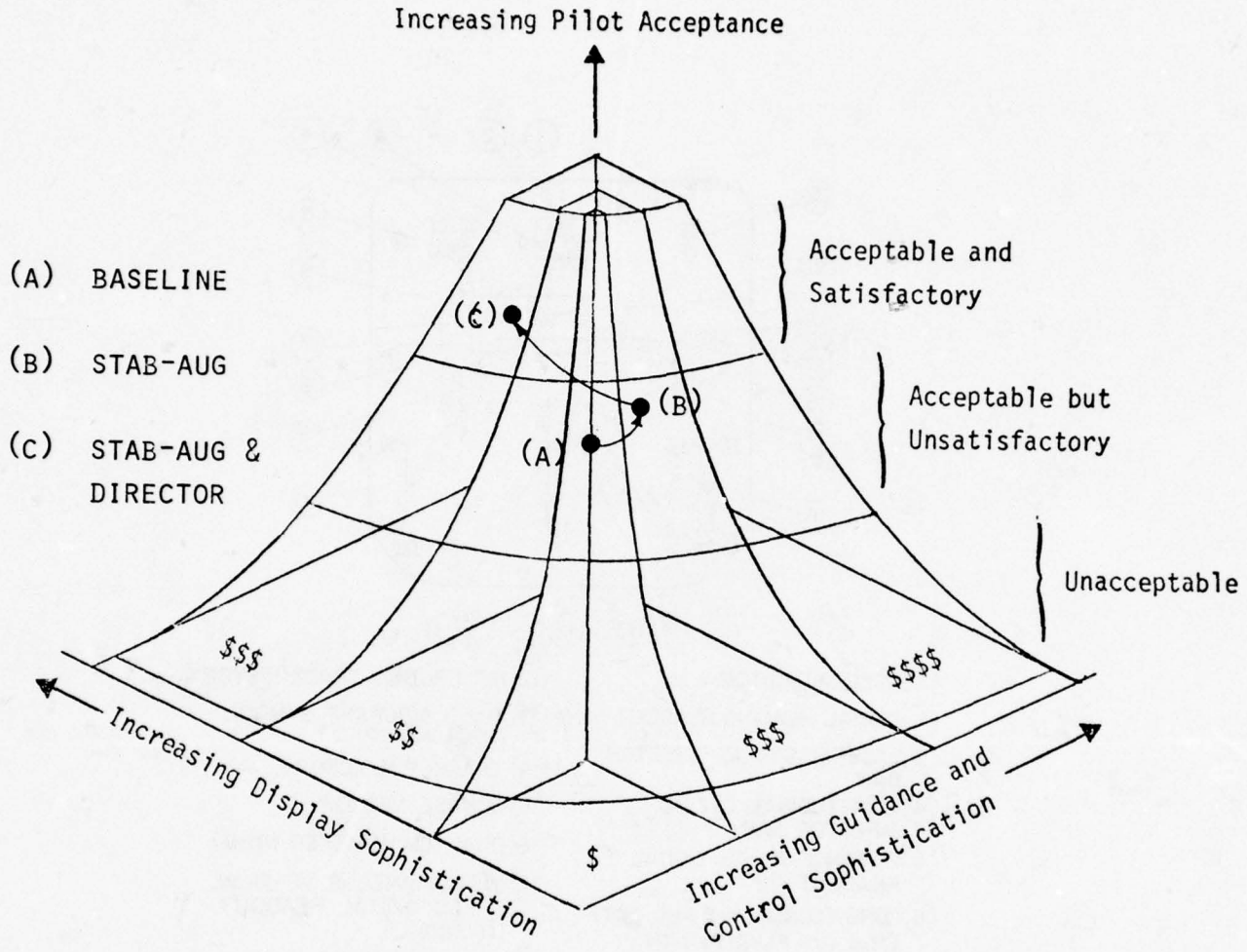
FRACTIONS OF ATTENTION: $f_{\sigma,\dot{\sigma}} = 0.43$ $f_{\psi,\dot{\psi}} = 0.19$ $f_{y,\dot{y}} = .26$ $f_{\phi,\dot{\phi}} = .12$

SLIDE (16)



(1) ROLL INDICATOR
(2) DIGITAL HEADING READOUT (deg)
(3) LATERAL CYCLIC DIRECTOR BAR
(4) LONGITUDINAL CYCLIC DIRECTOR BAR
(5) DISTANCE-TO-GO DIGITAL READOUT (ft)
(6) LONGITUDINAL (γ) AND LATERAL (σ) FLIGHT PATH ANGLE ERROR
(7) GLIDESLOPE ERROR (h) AND COURSE ERROR (y) "WINDOW"
(8) HEADING ERROR
(9) ALTITUDE DIGITAL READOUT (ft)
(10) TORQUEMETER (psi)
(11) HORIZONTAL SITUATION INDICATOR (HSI) EXTENDED RUNWAY CENTERLINE
(12) HSI GROUND TRACK HISTORY
(13) FIXED AIRCRAFT SYMBOL (HEADING UP)
(14) TRACK PREDICTOR
(15) COURSE VECTOR
(16) DUAL-TACHOMETER (RPM)
(17) INSTANTANEOUS VERTICAL SPEED DIGITAL READOUT (ft/sec)
(18) FIXED AIRCRAFT SYMBOL
(19) GROUNDSPEED ERROR (u)
(20) COLLECTIVE DIRECTOR "DOUGHNUT"
(21) ARTIFICIAL HORIZON (θ & ϕ)
(22) GROUNDSPEED DIGITAL READOUT (knots)

SLIDE (17)



$ - relative cost

THE CONTROL/DISPLAY PROBLEM

DISCUSSION

Robert Flynn: Would you explain your rationale in choosing the weighting factors in the quadratic terms (performance indices)?

Hess: Let me preface his question with the fact that anytime you use a quadratic synthesis procedure, it becomes a game in selecting the weighting coefficients in that index of performance. And, of course, from the pilot modeling standpoint, you want to select them such that you get a dynamically representative model of the human pilot. I know of no direct synthesis procedure to do that other than to rely upon experience and to determine beforehand what you think are allowable deviations in each of the variables. Now you can do that typically from the task description. If it's the landing approach task, he might take, for example, the dimensions of the Category II window. That may not be applicable to helicopter flight. Let's pretend it is. It gives you a handle on what you may consider as maximum allowable deviations for those. And you kind of approach it from that standpoint. Now there's a TMX (report) out that I wrote in which I go into more detail as to how one can choose these things. But again, I somewhat apologetically have to say that the procedure is based upon the experience of the person who's doing the analysis. The worst thing that can happen is that you can get a non-representative model of the human pilot that's not robust. In contrast, the best thing that can happen is to have a model that does indeed mimic the pilot's dynamic characteristics.

Irving Ashkenas: I was noticing that your pilot transfer functions appeared to have a tendency towards a higher gain in the higher frequency regions. Now when you mechanize that gain as, say, in flight director feedback, that would imply that they had a lot of high frequency content. It's been some of our experience that it's pretty disturbing to the pilot. In other words, the display becomes too busy. How do you handle that?

Hess: The human operator describing functions that you saw were for the unaugmented UH-1BH vehicle. I broke my own rule of not designing a stability augmentation system before designing a flight director. Those describing functions point out the fact that you had better design the stability augmentations system before you design the director because they were flat at high frequencies which means that the director really is bobbing about. The pilot can do a good job. He can do a better job than without a director, but he had better not look away. He had better not sneeze or drop a clipboard because if he does, things are gone very quickly.

VTOL FLIGHT CONTROL FOR ALL-WEATHER SHIPBOARD OPERATIONS

Dr. James A. Franklin

Chief, Flight Dynamics
and Controls Branch

NASA/Ames Research Center

Manuscript unavailable at the time of publication.

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V/STOL FLIGHT DYNAMICS

REQUIREMENTS FOR FUTURE RESEARCH

TECHNOLOGY NEEDS

- REVISE V/STOL FLYING QUALITIES CRITERIA
- INVESTIGATE FLIGHT CONTROL/DISPLAY CONCEPTS

PROGRAM APPLICATIONS

- POTENTIAL HARRIER IMPROVEMENTS
- V/STOL MULTI MISSION AIRCRAFT
- V/STOL FIGHTER
- CIVIL VTOL TRANSPORT

VTOL FLIGHT DYNAMICS RESEARCH

GENERIC VTOL RESEARCH (R AND T BASE)

OPERATION

- SHIPBOARD AND LAND BASED
- ALL WEATHER - ROUGH SEAS
- APPROACH AND VERTICAL LANDING
- SHORT TAKEOFF

FLIGHT CONTROLS

- CONTROL COMPLEXITY VS OPERATIONAL CAPABILITY
- SYSTEM RESPONSE REQMNTS
- COCKPIT CONTROL MECHANIZATION

DISPLAYS

- FORMAT AND CONTENT
- INTEGRATED WITH CONTROLS

SPECIFIC CONFIGURATION INVESTIGATION

- INTEGRATED PROPULSION FLIGHT CONTROLS
- POTENTIAL FUTURE IMPROVEMENTS TO HARRIER
- CONTRACTOR DEVELOPMENT AND NAVY SELECTION OF FUTURE VTOL AIRCRAFT
- CIVIL TRANSPORT CONFIGURATION DEVELOPMENT

CONTROL COMPLEXITY VS OPERATIONAL CAPABILITY

ATTITUDE CONTROL

- RATE DAMPING
- ATTITUDE STABILIZATION

VELOCITY CONTROL

- THRUST VECTOR
- ACCELERATION COMMAND
- VELOCITY COMMAND
  - ATTITUDE CONTROL
  - THRUST DEFLECTION

INTEGRATED PROPULSION/FLIGHT CONTROLS

WEATHER

- 700 FT CEILING
  1 NM VISIBILITY
- < 100 FT CEILING
  < 1/4-NM VISIBILITY

BASE OF OPERATION

- SHIPBOARD
  - CONVENTIONAL CARRIER
  - SMALL AVIATION SHIPS
- LAND
  - CIVIL AIRFIELDS
  - SMALL SITES

DECK MOTION

- UP TO 10^{o} ROLL
  5^{o} PITCH
  10 FT HEAVE

AIRFRAME/CONTROL SYSTEM RESPONSE REQUIREMENTS

ATTITUDE AND VELOCITY CONTROL

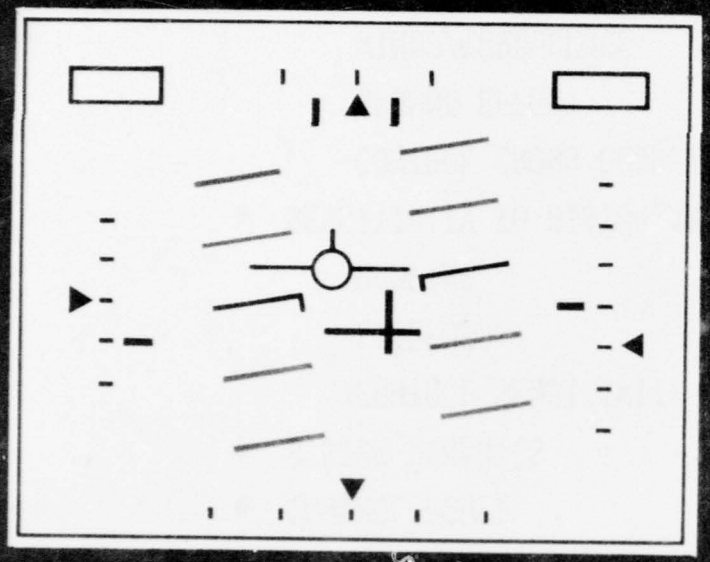
- CONTROL POWER
- SYSTEM DYNAMICS
  - CONTROL SENSITIVITY
  - STIFFNESS
  - DAMPING
- SENSITIVITY TO DISTURBANCES
  - CONTROL CROSS COUPLING
  - GROUND EFFECT
  - WINDS/TURBULENCE

INTEGRATED PROPULSION/FLIGHT CONTROLS

- CONTROL POWER VARIATION WITH BLEED
- CONTROL CROSS COUPLING
- CONTROL LAGS

DISPLAY REQUIREMENTS

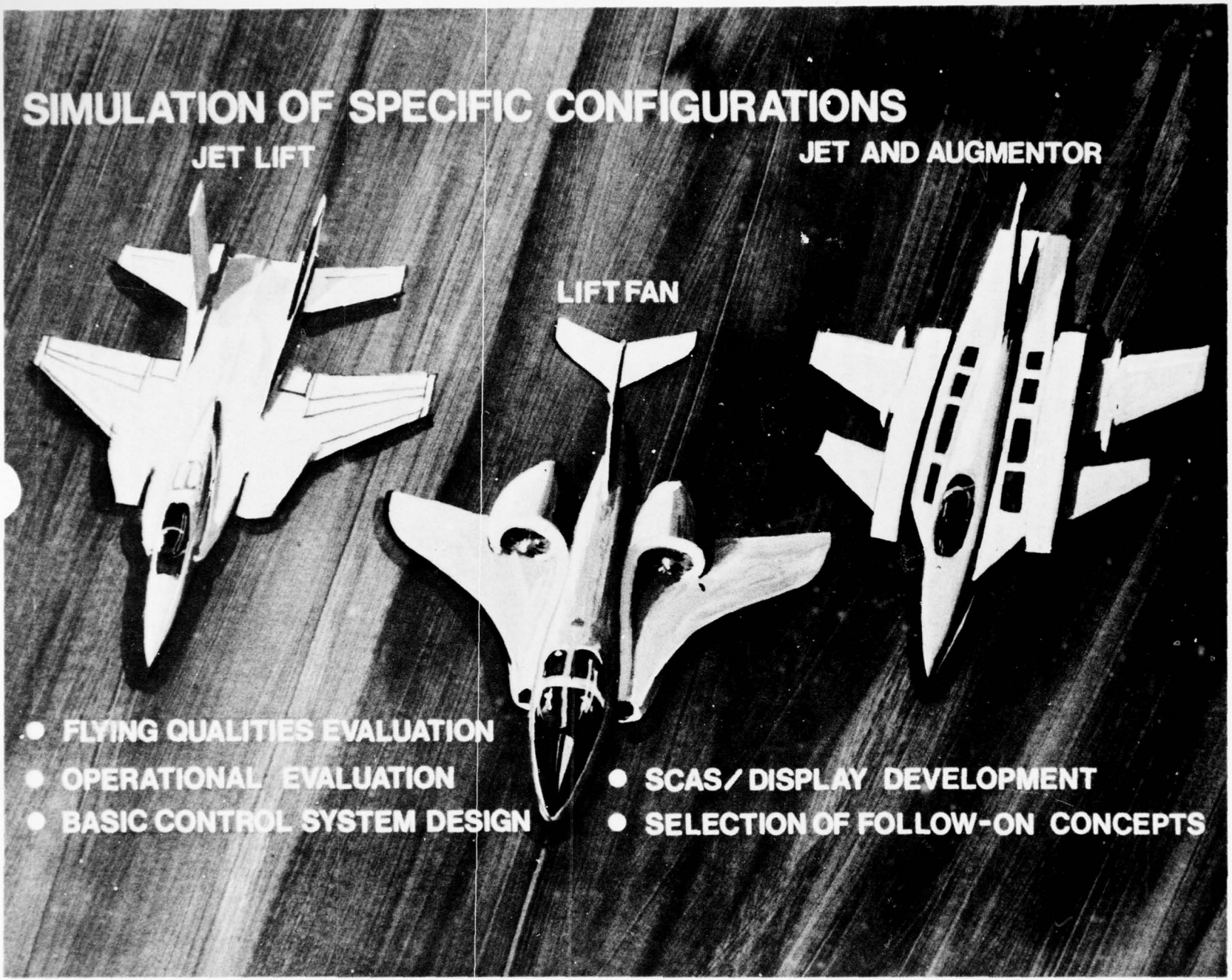
- THRUST VECTOR CONTROL
- VELOCITY COMMAND CONTROL



SITUATION



PERSPECTIVE


SIMULATION OF SPECIFIC CONFIGURATIONS
JET LIFT
LIFT FAN
JET AND AUGMENTOR
● FLYING QUALITIES EVALUATION
● OPERATIONAL EVALUATION
● BASIC CONTROL SYSTEM DESIGN
● SCAS/DISPLAY DEVELOPMENT
● SELECTION OF FOLLOW-ON CONCEPTS

DISCUSSION

Sam Craig: I have a question relative to your approach. You mentioned control power definition. This has been an albatross for many years relative to control power. I'd like to suggest that control power, per se, is very design specific. We've been trying for 20 years now to define what is required for thrust-to-weight ratio, angular acceleration command and the like. The thing that we have overlooked is the establishment of a definition for the factors involved when setting control power, for example, to gust sensitivity, trim characteristics, emergency situations and so on. I would like to know how you are going to address control power from your studies? Are you going to try again to define the specific thrust-to-weight ratio like presently in the specs, which presently is really a gross albatross?

Franklin: I think the important thing to consider is the control power required to maneuver. Any specific design is going to have its own trim requirements and we shouldn't be trying to deal with that. I don't think you can sort it out. The biggest unknown is what do you need in excess of trim to maneuver for a specific task. And that's what we should focus on. Thrust-to-weight means the same thing.

Craig: O.K. But are you going to concentrate also on defining how you put together the ingredients for defining an acceptable control power? In other words, what guide lines does listing the factors imply so that people are aware of what has to be considered? Maneuvering is one facet of it, but maneuvering is also subjected to the pilot's own opinion.

Franklin: Maneuvering, to me includes not just calm-air or still-air maneuvering, but also the other two points you mentioned such as maneuvering or correcting upsets in rough air and counteracting failures. I shouldn't say that this is an easy task, but you can by looking at a fixed design obviously determine what your control power requirements are for trim. We're not interested in saying what the total control power requirement is. Rather, it's defining that which is needed in excess of trim to handle the airplane control demands such as in hover over the deck when in ground effect (if you're going to try and do something with ground effect other than just come right down on the ship), to handle failures, or to handle the aircraft in turbulence.

Craig: I don't mean to belabor the point, but I would like to see NASA lead the way in making sure that the check list definition of what factors should be involved is verified in your experiments because right now the biggest single problem the designer has is in adhering to the rules such as, if the mil specs say 1.05, then that's all they include in the design. You may actually need a thrust-to-weight ratio of 1.05 or 1.1, but an individual design might be quite adequate to get by with 1.05 as the Harrier does under mission conditions. That's an area, I think, in which there is considerable effective work remaining to be done.

Franklin: It's the same thing as saying "umpity-ump" radians per second squared in roll acceleration. How can you divorce that from dihedral effects when you're going through a lateral translation?

Andie Byrnes: I have a comment along that line. I don't think the maneuvering task is defined by control power. The designer needs guidance on how to build the parts and some of the control criteria define the size of the aluminum pieces, while others, the size of the black boxes. Now there has to be some definite guidance on these things, I think, before you start cutting metal and before you know anything about your airplane. You must have guidance on both how to build a structure, and how to build up the electronics.

Franklin: Some of the work that's conducted in the wind tunnels out there obviously is more to the point of aiding the specific design. But let's face it, you designers know a lot more about cutting metal and that sort of thing than we ever will. I think we would waste our time and resources if we went into that business; if I understood your point right.

Byrnes: No, I wasn't talking about cutting the metal. I was talking about how big a piece do you cut out?

Franklin: I mean the specific design of how you get it. Now some of the wind-tunnel tests can obviously help that. But you people know a lot better than we do about how to go about obtaining it. If we can provide any kind of generalized guidance on how much you might need, I think that's more important.

Irving Ashkenas: If I may say so, I think what both of these gentlemen were shooting at was the interaction between the various kinds of requirements: those stemming from maneuvering; those stemming from turbulence regulation; those from trimming; and also the flight control system effects on those requirements. For example, we heard yesterday that a large part of the CL-beta effect upon roll was due to tilting the airplane. It wasn't that you were maneuvering in ground effect; it was just a side thrust, and you never did tilt the airplane. Presumably that would have a big effect on your roll control power requirement. I think putting those things together in some tangible and systematic way is what we really need. We still don't know how to superimpose maneuverability requirements with trim requirements and regulation requirements. How do all those add up to give you the final control power? Is that a fair statement?

Daniel Cichy: You people said these same things about ten years ago at another VTOL conference, and I guess it still applies. I agree with the comments made in regards to control power. We've looked at control power for 20 years and have all kinds of numbers. Now, what we really need to define is items such as the turbulence field we have to operate in. We talked about that yesterday and spotted the gaps there.

Franklin: That's an important one.

Charles Abrams: Jack, you mentioned increasing the control complexity as related to sensor complexity. Have you done any theoretical studies on sensor complexity?

Franklin: No. Our program is experimental, not theoretical. The redundancy question is a valuable one to answer. It's not one that we propose to answer in this program. I think, as you well know, there's work going on in the Navy on that. There's work in other groups at Ames looking at the same questions. The question, as a matter of fact, came up yesterday also, in terms of the guidance requirements for some of these things. My group is not specifically addressing that question either. Just to reiterate the point, we're looking at the operational capability to be derived in simulation and propose to do the same in flight. If you have to make it redundant, or if you have to have better sensors to have the actual capability, you'll know that as well. Somebody has to solve that problem. We recognize it, but we're not proposing to get into that in this program.

Wallace Nelson: Is NASA possibly planning to go ahead and look at the additional element of the shifting inside the entire system utilizing the advantage of the shift as an integral part of the control loop aid in the vehicle design considerations?

Franklin: No. A very straightforward answer. At least as far as our group is concerned, I don't think we're smart enough to do that. We can look at the aircraft oriented side. It's a point well taken, that was made yesterday. You can obviously do a good bit to help the problem there. There's obviously a trade.

Jack Stephens: The fundamental part of my question is: how far back do you go in selecting the control laws that are to be mechanized? For example, we know that a velocity control works great for a heavy lift helicopter or for shipboard operations. However, it may result in compromises for the remainder of the mission. How do you initially select the control that will be optimal?

Franklin: Well, part of the mission that we're going to look at is terminal area operations such as transition down to landing and conversion following takeoff. For example, the work that was done the other day, indicated that you can successfully operate a system like that. It was shown that a decoupled velocity command system could successfully operate the airplane through conversion down to hover, and so forth, by properly bldnding the (control) laws from one phase of flight to the other. Presumably, when you're in conventional flight, utilizing the airplane for its actual intended mission such as combat, surveillance, or whatever, you're going to phase those controls out because you've got something akin to a conventionally operated aircraft. It may not be true if you want to take into consideration some air combat capability. You may want to provide that capability in the system, too. At least, I emphasize the point that we're not looking at that. But it's a point well taken. The system certainly has to accommodate to that, and I think it can be made to do it.

SURVEY OF PILOTING FACTORS IN V/STOL AIRCRAFT WITH IMPLICATIONS FOR FLIGHT CONTROL SYSTEM DESIGN*

Robert F. Ringland and Samuel J. Craig
Systems Technology, Inc.
Hawthorne, California

INTRODUCTION

A recently completed literature review (Ref. 1) identifies excessive pilot workload as a major problem requiring solution in future V/STOL aircraft design. Past development history points out several causes for excess workload, most of which are rooted in the nature of the V/STOL concept and the missions such an aircraft is uniquely capable of performing. Thus, in developing the flight control and display concept for new aircraft this problem area, i.e., excessive pilot workload, must be addressed and play a governing role.

The paper identifies the flight control system design factors involved for workload relief using the results derived from the review. Briefly speaking, V/STOL operational capability requires full use of the current technology base (e.g., fly-by-wire, integrated display, microprocessors) for effective pilot utilization of the vehicle. The underlying reasons cited herein provide a consolidation of the key "lessons learned" from the piloting factors viewpoint. With this knowledge, it is hoped that the requirements associated with the V/STOL-unique features and configuration-specific design qualities (e.g., conversion controls and associated procedural features, variable stability characteristics, etc.) can be made more apparent to flight control system designers and human factors engineers, with the result that more effective pilot control of these aircraft can be achieved in the future.

The material reviewed covered the last fifteen years or so and included both papers and formal technical reports. The subject matter included flight test programs, simulator studies, analytical studies, and previous technology summaries. Aircraft programs of major interest included the Harrier (unique because of the considerable operational experience gained), the XC-142 (an operational evaluation prototype program wherein IFR capability was demonstrated), the XV-5 (lift-fan concept), and the VAK-191B (recent Navy evaluation and functional similarity to certain proposed V/STOL concepts). Experiences with other aircraft were also included where the material was available and pertinent. The paper proceeds from general V/STOL concept-related considerations, through specific

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aircraft realizations, to the development of the major aspects of the V/STOL workload problem and the associated implications for flight control system features.

GENERAL CONSIDERATIONS

All V/STOL aircraft have certain inherent characteristics held in common as summarized in Table 1. The central characteristic is noted first — the V/STOL conversion between aerodynamically supported (and controlled) flight to thrust-supported (and controlled) flight. All other V/STOL-unique characteristics, including human factors aspects, stem from this property. Its characteristic capability of landing and taking off from a small area, the need for altering its configuration (principally net thrust vector magnitude and direction), and its relative inefficiency in terms of fuel consumption are all inherent in the concept.

A major implication of the conversion flight regime is the need for some form of aircraft configuration scheduling. The physical configuration of the aircraft must be varied in some fashion; vertically directed thrust forces must be rotated to the near horizontal and their magnitude reduced (typically) as the aerodynamic lift builds up. The buildup of aerodynamic lift at relatively low airspeeds generally implies aerodynamic configuration changes, e.g., flaps, stabilizer trim, etc. In short, the trim state varies continuously and relatively rapidly as the aircraft slows down or speeds up.

TABLE 1

V/STOL-SPECIFIC GENERIC CHARACTERISTICS

Conversion Between Aerodynamically Supported and Thrust-Supported Flight
● Configuration scheduling and trim (energy) management
● Fuel efficiency
Extensive Vehicle (Controlled Element) Variations
● Changes in control technique, controlled variables
● Control redundancy
● Stability characteristics
Unusual Sensitivity to Disturbances
● Wind, wind shear, and crosswinds
● Ground effects
● Configuration changes

Providing vertical takeoff and vertical landing capability imposes design penalties relative to conventional airplanes in terms of propulsion/lift system weight and fuel requirements. Minimizing the latter calls for spending as short a time as possible in the thrust-supported flight regime. At takeoff, this means a near-maximum performance takeoff to quickly build airspeed; for landing, it implies delaying the deceleration as long as possible, then decelerating at near-maximum capability. The former is easy enough, while the latter ideal can only be approached under visual flight reference (VFR) conditions and has not proven feasible under instrument flight reference (IFR) in contemporary V/STOL aircraft design practice, primarily because of excessive pilot workload. In any event, a low fuel state has more profound implications for the approaching V/STOL aircraft in contrast to the conventional airplane because a larger percentage of the total fuel load must be reserved for the approach and landing in the vertical landing mode.

Furthermore, there are fundamental aerodynamic and propulsion system limitations on how fast the V/STOL aircraft can descend in a controlled fashion or, given a desired approach path angle, how rapidly the aircraft can decelerate along that path. For example, a given steady path angle is equivalent also to an instantaneous acceleration and a different path angle in accordance with the general trim condition:

$$(T_X - D)/W \doteq \gamma + a_X/g = \text{Constant}$$

See Ref. 2 for additional implications for manual control imposed by these constraints.

In sum, the conversion capability of the V/STOL aircraft carries with it implications of how it can be used most effectively within the constraints imposed by fundamental performance limitations, fuel efficiency, and the pilot's ability to stay "on top of the airplane." The latter (soft) constraint is the important driving consideration in the V/STOL's control system design.

The second item in Table 1 refers to the V/STOL's unique characteristics as the controlled element in the pilot/vehicle closed-loop system. These also stem from the conversion. A change in control technique is required, e.g., pitch attitude changes alter flight path angle in conventional flight, but alter forward speed in hovering flight. The controlled variables of interest are velocities (airspeed, path angle) in conventional flight, but positions (relative to a desired landing spot) in hovering flight.

The V/STOL aircraft close to hover is inherently unstable in its attitude and often in both path and speed responses. This is in contrast to the conventional aircraft which usually has some measure of stability — the pilot can trim the vehicle to a desired reference (e.g., attitude or speed) and take his hands from the controls for some seconds to attend to other tasks.

The third item in Table 1 refers to the V/STOL-unique disturbance characteristics. The V/STOL, because of its slow speed in the conversion flight regime, is more strongly affected in its path responses by wind shear and crosswinds than its conventional counterpart. Thus, there can be large path changes in shears, and large crab angles in crosswinds. There is also a stronger requirement for ground-referenced speed information during the final stages of approach to a landing.

Ground effects for the V/STOL aircraft encompass altitude and attitude related force and moment disturbances, ingestion of hot gases (which leads to loss of thrust), and visual field disturbances (dust clouds, spray), all of which are inherent in the high velocity, downward-directed jet exhaust or lift fan (or propeller) downwash.

The configuration change required to begin conversion to the thrust-supported flight regime can be a profound disturbance to the pilot's control of path. In many cases, it is inherent in the concept — starting lift engines, switching to fan or augmentor modes. In others it results from the discrete manner in which the configuration is changed — initial wing tilt on the XC-142 or CL-84, large initial nozzle angle changes on the AV-8. Regardless of source, it requires coordinated maneuvers or parallel control inputs to suppress, or it results in substantial disturbances in flight path, particularly in the context of precision instrument approach.

Taken together, these considerations illustrate that for the V/STOL aircraft, fewer things "take care of themselves" and more things change relatively rapidly and require attention. The result is an increase in the number of control and stabilization functions which must be performed by the pilot/vehicle system in the V/STOL (that is, partially thrust-supported) modes of flight. Hence, the question from the design viewpoint is one of appropriately assigning functions to the pilot or to the vehicle and its subsystems to achieve adequate system performance at workload levels acceptable to the pilots.

CONTEMPORARY PRACTICE

The considerations of Table 1 are all general to the V/STOL concept. Some specific contemporary aircraft realizations are listed in Table 2. The first six entries are in the jet-lift category and employ various combinations of engine types. The classification scheme is based on propulsion/lift system concepts and the associated implications for engine and configuration control during hover and conversion.

Many of these implications for management and control are noted in the third column of Table 2. There are a wide variety of schemes used for control of configuration and propulsion/lift systems. Collectives and throttles (occasionally both) are used for propulsion and/or lift control; levers or beepers (which operate similar to trim buttons) are used for configuration control. This comes about because of differences in configuration and differences in the design teams' resolution of the collective (helicopter) versus throttle (conventional aircraft) controversy.

TABLE 2. V/STOL AIRCRAFT CONFIGURATIONS

Category	Aircraft	Lift/Thrust/Configuration Control	Conversion/Hover Augmentation	Special Features/Remarks
Lift jets plus cruise jets	SC.1	Collective — lift engines thrust Twist grip — cruise engine thrust Beeper — lift engine tilt	Pitch/roll rate damper	Complex engine start/stop procedure Pitch trim change on engine start/stop Def. lateral/directional H.Q. during conv.
	Mirage III-V, Balzac	Throttle — lift engines thrust Throttle — cruise engine thrust	3-axis rate damper	Pitch trim change on lift engine start/stop Def. lateral/directional H.Q. during conv.
Lift/cruise jets plus lift jets	VAK-191B	Throttle — lift engines thrust Throttle — lift/cruise engine thrust Nozzle angle lever with adj. stop	3-axis rate damper Pitch/roll attitude (fly-by-wire system)	Def. display/control design for engines Complex system failure diagnosis Poor indication of system safety margin
	VJ-101C	Throttle — all engines Beeper — pod tilt	3-axis rate damper Pitch/roll att.	"Very heavy" workload in hover and conversion; takeoff and landing
	DO-31	Two throttles — lift/cruise engine thrust Throttle — lift engine thrust Nozzle angle lever	3-axis rate damper Pitch/roll att. (full auth. SAS)	Complex and demanding procedural reqm'ts; (apparently requires two pilots to fly) SAS cuts out on full stick deflection
Lift/cruise jet	AV-8A, P.1127, Kestrel	Throttle — lift/cruise engine thrust Nozzle angle lever with adj. stop	3-axis rate damper with "leaky att." Sideslip augmenter	Workload constrains approach procedures IFR not permitted below 120 knots — deficient stability
Lift fan	XV-5	Collective — fan lift Twist grip — thrust (fan mode) Throttle — thrust (cruise mode) Beeper — louver angle (fan mode)	3-axis rate damper	Complex conversion scheduling/procedures Def. blending of control force generators Deficient stability qualities Auto. power reduction to avoid fan overspeed
Tilt-wing	XC-142	Collective — blade angle (V/STOL) Throttle — power (cruise) Beeper — wing tilt/flaps Tail propeller controls	3-axis rate damper Pitch/roll att. Vert. speed damper RPM governor	Complex lift/propulsion system procedures Ballooning upon initial wing tilt Demonstrated IFR operation
	CL-84	Throttle — power and blade angle Beeper — propeller rpm Beeper — wing tilt Tail propeller controls	3-axis rate damper Pitch attitude RPM governor	Ballooning upon initial wing tilt — difficult to maintain precision in control of speed and path Insufficient path damping
Tilt duct	X-22A	Collective — blade angle or Throttle — power. Beeper — duct angle.	3-axis rate damper RPM governor	Problems with trim and stability during conversion; attitude and collective coordination required to maintain level flight Extensive flight research
Augmenter	XV-4A	Throttle and diverter valve controls.	3-axis rate damper	
	XFV-12	Throttle and diverter valve controls.		Under development — engineering appears oriented toward minimum FCS complexity

The display aspects of these aircraft have not been specifically addressed in Table 2, largely because they were conventional in both form (barring the Harrier's head-up display and certain research programs) and flight situation information content. The differences in configuration and propulsion scheme listed in Table 2 imply differences in the associated propulsion system instruments. Multiple engine aircraft generally had multiple instruments — consider the DO-31's ten engines!

Other display differences related to the perceived needs for flight-safety-related displays. Thus, sideslip and angle of attack are prominent on those configurations sensitive to sideslip-induced roll divergences in hover and conversion (the XV-5 and all jet-lift except the DO-31 and VJ-101C).

Table 3 summarizes past practice as typified by these V/STOL aircraft. The controls and displays reflect the designers' motivation for simplicity and "flexibility" (e.g., redundant controls to be "sorted out") with the minimum of automation, and dependence on the pilot's high level of flying skill to achieve system safety and performance. For the most part these were research programs whose prime objectives were seen as demonstrating proof of propulsion/lift concepts in a limited number of flight vehicles with highly qualified test pilots. The piloting functions required are as listed. These functions are typical of conventional aircraft as well — but only in kind, not in magnitude. In the V/STOL aircraft, each of these functions is more demanding than its conventional aircraft counterpart.

The result is an excessive dependence on the pilot. He is overloaded in his perceptual, cognitive, and psychomotor faculties by this excessive reliance on the pilot protion of the V/STOL pilot/vehicle system. The result is excessive workload in many portions of the V/STOL mission: takeoff, hovering, and approach, particularly precision IFR approach.

TABLE 3. SUMMARY OF PAST V/STOL DESIGN PRACTICE

Controls and displays reflect desire for:

- Simplicity of hardware
- Maximal "flexibility"
- Minimum automation
- Safety and performance through pilot

Piloting functions include:

- Configuration scheduling; lift/thrust management
- Attitude stabilization (in most cases)
- Engine failure management (in most cases)
- Path, speed, and position control or regulation

This result has been well recognized for a number of years and is no surprise. It is the central result and main theme of the literature review. The key problem for the human factors and flight control engineers in future V/STOL designs is in assuring adequate performance at acceptable pilot workload levels.

MAJOR WORKLOAD CONTRIBUTORS

The implications for future V/STOL flight control system design may be addressed from the standpoint of alleviating pilot workload, particularly in those areas where past design practice has resulted in heavy demands on the pilot. It is therefore appropriate to consider the major contributors to pilot workload.

In this paper we address two — that associated with configuration management and control, and that associated with aircraft stability and response qualities. With regard to the first, consider Table 4. This table may be summarized by noting that the pilot has redundant controls for selection of operating point — speed and path angle. This is particularly true on a dynamic basis; long-term responses differ from short term. In any event, the pilot has difficulty in getting the aircraft to do what he wants; the responses are coupled and tend to be non-separable. He cannot get a speed change without upsetting attitude or path (e.g., initial nozzle tilt results in "ballooning").

That there really is a control-related or task-complexity-related workload problem can be inferred not only from flight test reports, e.g., Ref. 3, but also from recent operational V/STOL accident experience.

TABLE 4. CONVERSION SCHEDULING AND CONTROL

Current Design Practice — Multiple manipulators governing magnitude (throttle or collective) and angle (lever or beeper) of lift/thrust vector)
Consequences — Piloting problems in the form of: ● Control redundancy (attitude and vector) ● Coupled non-separable or non-partitionable responses in speed and path
Current Solutions — Flight procedures which: ● Avoid regime of control confusion (e.g., Harrier) ● Avoid changes in aerodynamic lift with speed

Figure 1 shows the accident rate experience through mid June 1976.* Contrary to the typical experience (dotted trend line) upon introduction of new aircraft, the current V/STOL trend (bold line) shows an increasing accident rate. These data represent 21 accidents, 14 of them major. Sixteen occurred in the V/STOL flight regime (conversion flight, landing, or takeoff). Of these sixteen, eleven had "pilot factor" as a contributing cause. The intended implication is that there also may be a "design factor," in particular, a system design factor which contributes to this result.

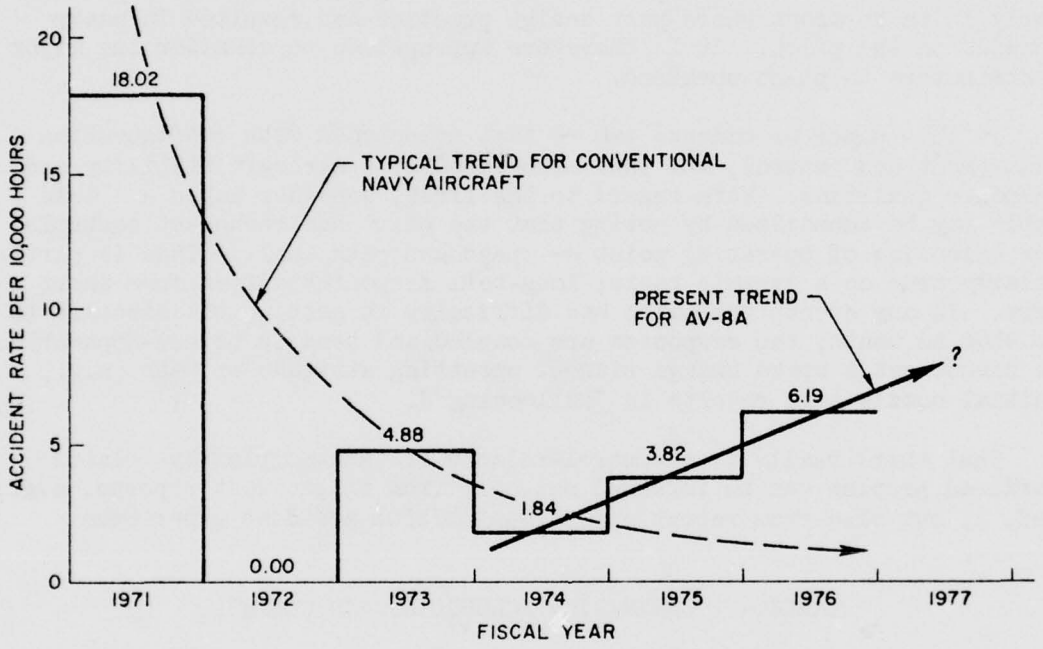


Figure 1. Accident Rate for AV-8A V/STOL Aircraft*

The conversion management for the Harrier is accomplished manually using the unique throttle/nozzle quadrant shown in Fig. 2. This unit has proven functionally reliable and is considered to represent good human engineering practice — despite the apparent manual control difficulties and accident rate data cited above. However, the key constraint that this or other such manipulator units impose is that the pilots may only attend to the conversion control serially. That is, the pilots manipulate these two powerful controls, throttle and nozzle angle, sequentially. Yet

*These data were provided by Curt Sandler of the Navy Safety Center. He states that through the end of August 1976 the rate was 9.1 (FY 1976 plus two months of FY 1977).

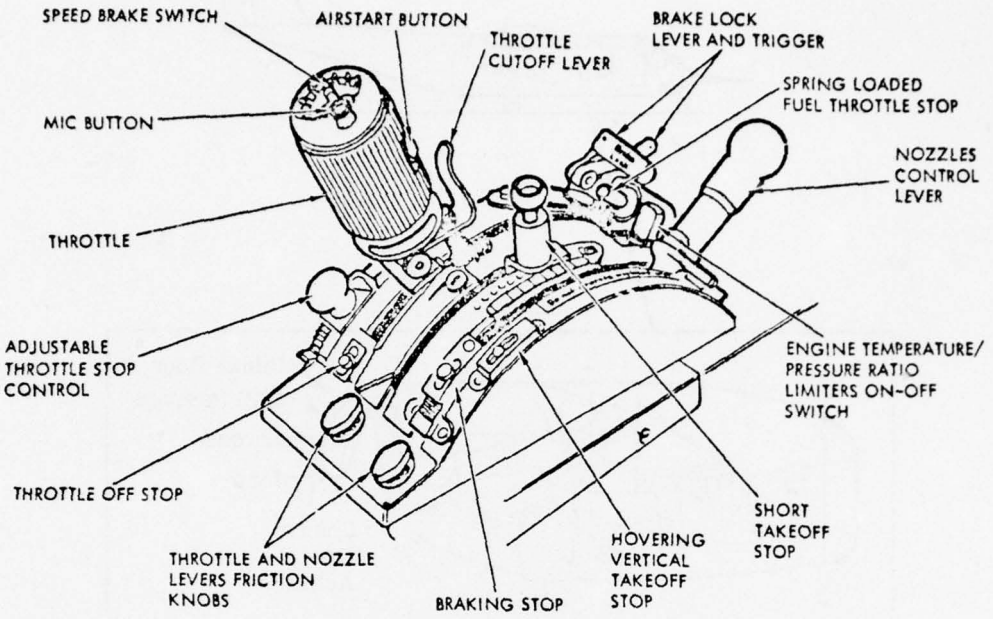


Figure 2. AV-8A Throttle/Nozzle Quadrant (Ref. 4)

neither control is "pure" in that both speed and path are changed (albeit in different ways) by either control. This fact alone implies that it will be difficult to conceive a manual conversion scheme which will allow the V/STOL aircraft to follow an arbitrary trajectory or path. Consequently, an automatic or semiautomatic system which can attend to the configuration changes and conversion controls in a parallel manner appears to be the more likely solution to the conversion problem of previous V/STOL aircraft.

Further complicating the control of the V/STOL aircraft in the conversion flight regime are the redundancy aspects, i.e., there is more than one control which can bring about a change in the controlled variable. Thus, both pitch attitude and thrust angle can produce a speed change in hovering flight. In the conversion flight regime the pilot controls both airspeed and path angle with three controls: pitch attitude, thrust magnitude, and thrust direction. This redundancy, when coupled with the difference between the short-term (dynamic) and long-term (trim) responses of the aircraft to the conversion controls, is often confusing to the pilot.

For example, consider the STOL research aircraft illustrated in Fig. 3. It has an elevator, a flap, a nozzle, and a throttle for longitudinal control. As shown in Fig. 4, the presence of these multiple control points permits the aircraft to be trimmed for a given steady speed

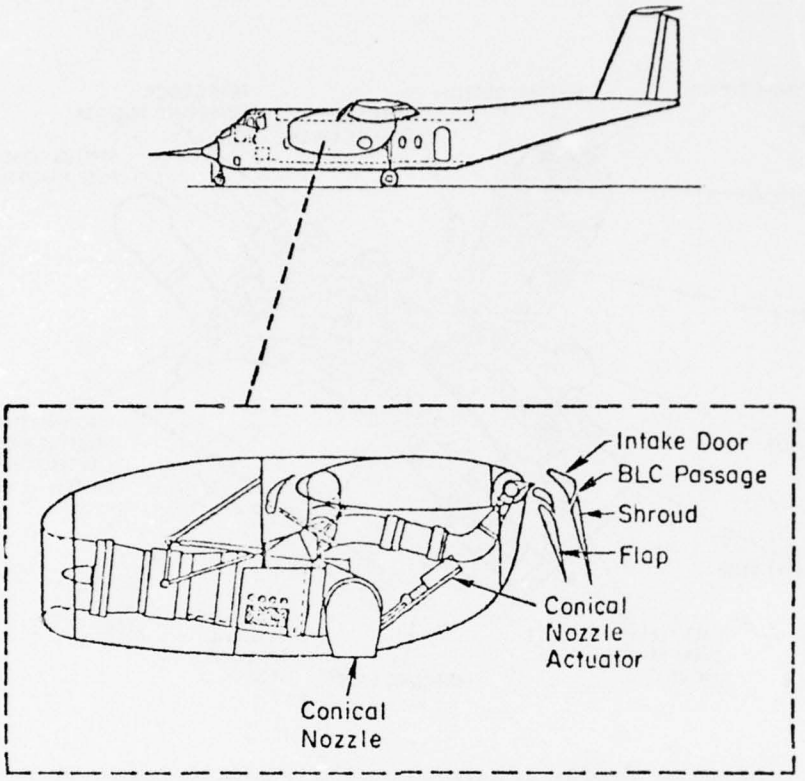


Figure 3. Augmentor Wing Jet STOL Research Aircraft (Ref. 5)

and path angle, using any one of a very large number of control combinations. The bounds in this figure are either physical limits (e.g., $\delta F_{max,min}$, $\delta_{vmax,min}$, $\delta T_{max,min}$) or areas where flight safety or comfort is deficient (e.g., α_{stall}, θ_{min}). This is the "trim space" for one speed and one path angle.

The wide range of possible trim conditions would seem at first glance to be highly desirable from the standpoint of operational flexibility. But, when available incremental performance, safety, and handling characteristics about possible trim points are considered, much of the total available trim space is neither safely nor comfortably usable — and this trim space is therefore narrowed down into a "desirable region," such as that indicated in Fig. 5. The overall operational window and the enclosed desirable region change with speed and path angle. Thus, plots similar to Fig. 5 can be made for each combination of speed and path angle. Given an approach path angle, the desirable regions at each speed in a decelerating conversion can then be connected to form a corridor of desirable trim states. This conceptual form of a conversion control scheduling system is shown in Fig. 6.

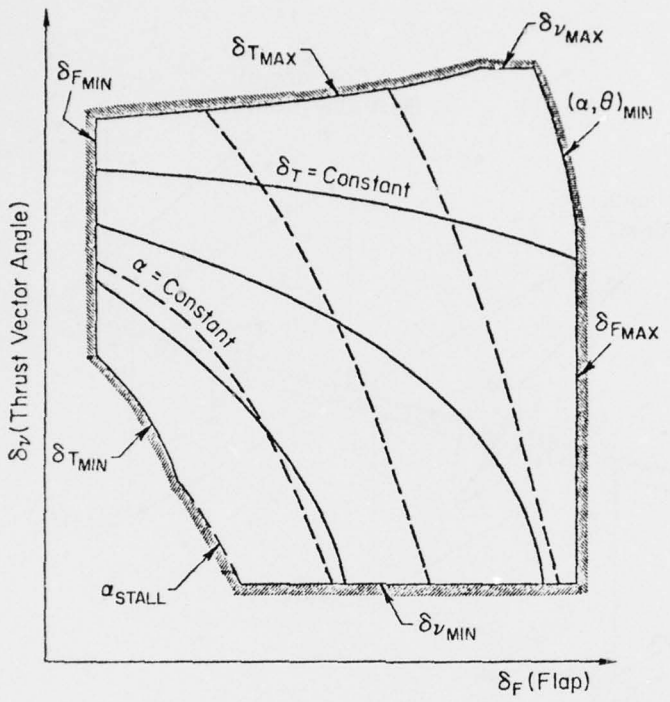


Figure 4. "Typical" Control Redundancy for Fixed Speed and Path Angle (Ref. 6)

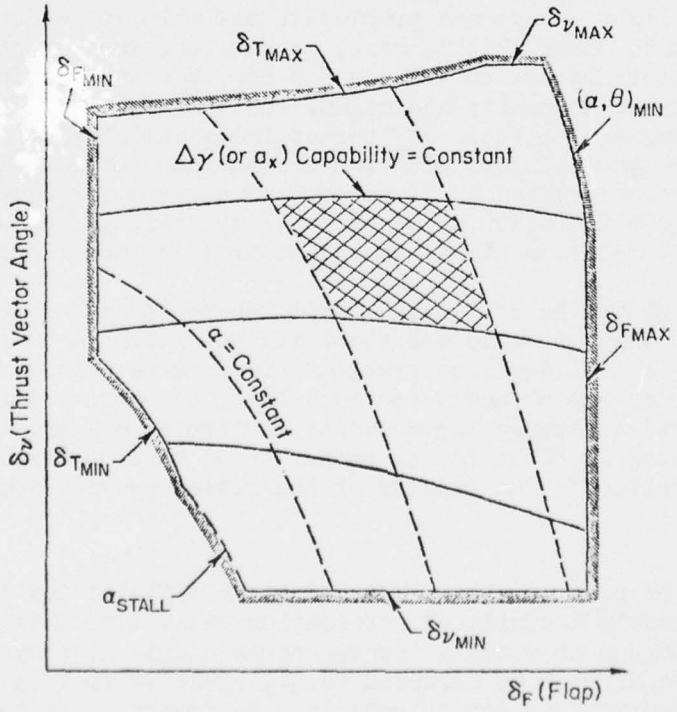


Figure 5. Desirable Region for Fixed Speed and Path Angle (Ref. 6)

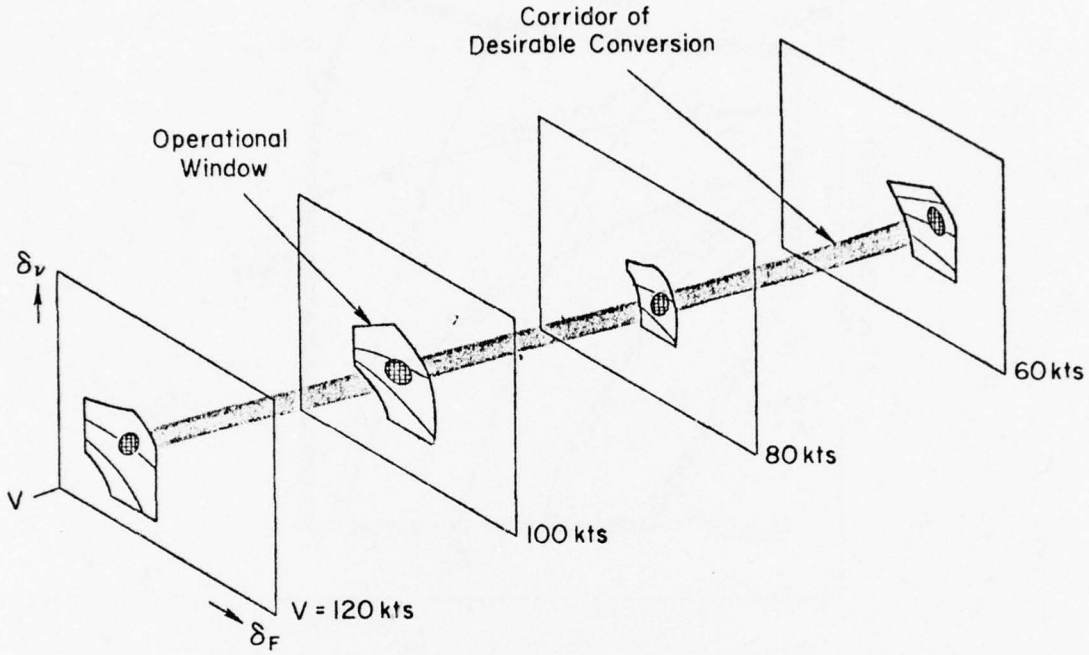


Figure 6. Configuration Schedule — Generic Example (Ref. 6)

The basic flight management problem in all this is to define the desirable regions. Once this is done, we have the further problem of defining what controls are to be used and how this utilization is to be partitioned between automatic and manual control. Unfortunately, the configuration parameters (lift, drag, thrust inclination, etc.) which set the trim also govern the path dynamics and closed-loop control. In other words, there are close connections and interactions between the equilibrium point (trim) control configuration and the resulting small perturbation aircraft dynamics which constitute stability and control characteristics (Ref. 6).

This leads us to the consideration of the second major contributor to pilot workload, that of deficient stability and response qualities. One solution to the V/STOL workload problem which has been pursued extensively is that of display improvement, the idea being to improve the overall system characteristics through improvements in display design.* The usual question addressed is "What is the proper trade between display design and control augmentation?" The results of the review provide some indication

*The review of past practice showed display deficiencies in the presentation of readily assimilated information related to flight safety. The V/STOL pilot has no readily interpretable single displayed quantity analogous to the display of airspeed (e.g., relative to V_{stall}), in a conventional aircraft, or rotor speed in a helicopter. He is therefore uncertain of his ability to arrest his rate of sink.

and are well illustrated in Fig. 7, which represents a revision to a figure appearing in Ref. 7 and (in this instance) pertains to the V/STOL precision instrument approach task. It shows that the region of tradeoff between sophistication of controls versus sophistication of displays lies well to the right of previous conceptions. The interpretation is clear; without attitude stabilization one cannot get an acceptable rating regardless of how sophisticated the display is. Without some degree of path (and speed) stability, and the ability to control these variables independently of one another, one cannot get satisfactory ratings, again regardless of the degree of display sophistication. Past these points one enters a region where there is a control/display tradeoff. In sum, the figure states that a control/display tradeoff does not exist until certain minimum levels of vehicle stability and controllability are satisfied. These minimum levels are somewhat above the "best" contemporary V/STOL designs for precision IFR approach. A sophisticated, integrated, even head-up, display will not overcome these deficiencies without excessive pilot workload.

The fundamental reasons for this are associated with pilot workload. The pilot is limited in the number of rapid, simultaneous, coordinated control activities which can be carried out, i.e., multiple stabilization and control tasks are difficult to manage. Thus, past designs are unforgiving of lapses in pilot attention to the major flight control tasks. He finds it difficult to attend to the ancillary tasks of flying; he can ill afford to take his eye off the primary displays, at least under IFR conditions. In short, past practice is characterized by an unwarranted dependence on the pilot; stability and response qualities are achieved through the pilot's eyeball rather than through the FCS design.

IMPLICATIONS AND CONCLUSIONS

The preceding discussion clearly implies certain flight control system design features for future V/STOL aircraft. These features will center upon the reduction of pilot workload. In particular, "simplification" of the manual configuration management task, and stabilization of both attitude and path responses are key items of workload relief. Further implications center on control blending and scheduling to purify the responses of the resulting controls. The major items of these design implications are summarized in Table 5.

Because of the unique features of the V/STOL aircraft in integrating its propulsion system and aerodynamic configuration, it is apparent that the vehicle has certain features which are common to control-configured vehicles. In fact, one could say that the V/STOL, in the conversion flight regime, is a control-configured vehicle. This carries with it the additional implication of an augmentation system to fully take advantage of this CCV-like character — the fly-by-wire concept. Mechanical integration of such systems, as has been tried in the past, has been in most cases detrimental to the control of the aircraft. Such being the case, a properly designed digital fly-by-wire stability augmentation, configuration management, and configuration control scheme would seem to go a long way toward the solution of the V/STOL workload problem.

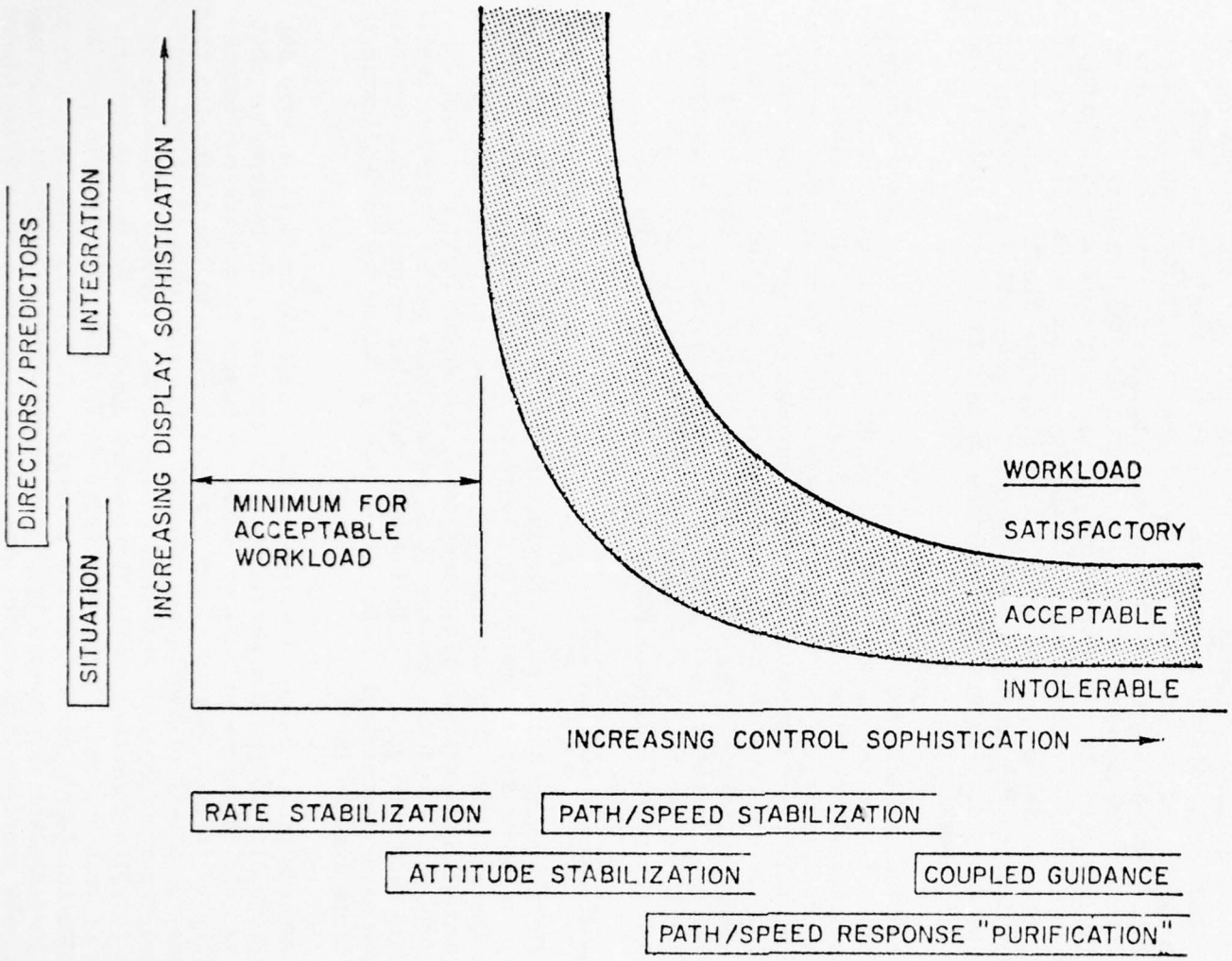


Figure 7. Control/Display Tradeoff for V/STOL Precision Instrument Approach

TABLE 5

FLIGHT CONTROL DESIGN IMPLICATIONS

Automated Configuration and Trim Management
Provides separable responses in speed and path (or their equivalent) throughout conversion
Augmented Stability
Attitude, path, and speed responses
Control Blending and Scheduling — Aerodynamic and Reaction (or Similar) Controls
Complex interaction
Difficult with mechanical integration
Summary — CCV-Like Flight Control Requirements
Implementation functionally similar, e.g., digital fly-by-wire

Table 6 notes the important conclusions of this paper with regard to workload relief in future V/STOL designs. They may be briefly summarized in the following statements:

- The well-recognized problem of excessive pilot workload in critical V/STOL piloting tasks has its roots in the control aspects of the aircraft: deficient stability and response qualities.
- These deficiencies cannot be overcome by display improvements alone, for these imply too much critical information processing by the pilot, leaving insufficient pilot capacity for the ancillary flying tasks.
- These deficiencies can be overcome and pilot acceptance won with existing demonstrated technology in automation and augmentation of the basic aircraft.

The evidence supporting these conclusions is massive and includes past experience with flight hardware, simulation programs, and analytical studies, not tomention current V/STOL operational experience. Thus, the specific implementations for alleviating past deficiencies can be called out with a high degree of precision based upon past experience in both its positive and negative aspects.

TABLE 6. CONCLUSIONS

Dominant Pilot Factor in Past Designs is Excessive Workload
● Control and Management Aspects — deficient stability response qualities (attitude, path, and speed)
● Display aspects — deficient safety margin information (e.g., lift margin near hover)
Display Improvement Alone — Insufficient
● Pilot limited due to inherent neuromuscular system properties
● Too much critical information processing by pilot
● Intolerant of pilot lapses (e.g., ancillary tasks)
Control Response Improvement Possible with Current Technology
● Acceptable to pilots (e.g., CCV)
● Versatility for V/STOL range of operating points
● Past experience (V/STOL, helicopter, CCV, etc.) provides guidelines for functional and performance requirements

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DISCUSSION

Robert Woodcock: Other than subjectively, how do you define "pilot workload"? It's an important factor behind all of your conclusions, and one that's kind of bothersome for many people.

Ringland: That is a rather difficult question to answer. Generally speaking, you can define it in the particular situation that you happen to be in and correlate it with pilot opinion; you can measure his physiological responses, and you can do all sorts of things in an attempt to quantify "pilot workload". The particular question that you have asked has been troubling people for a good number of years. I don't have any straight answers for you. Perhaps someone else might be able to offer some opinions for you along these lines. Sam..

Craig: Bob, although maybe not totally quantified, we do get a very good example of the workload facet of the problem. I don't know that we have to go to the detailed definition that quantifies a scale. We have the AV-8A as a very classic example of a workload saturation situation for the pilot. This is real. You can ask the pilot; you can observe the performance; and you can see the action break, so you know that that is an end point for our particular situation. Tom Lacey described the situation on the AV-8A in regard to their operational capabilities. He has identified instabilities and other features that are exactly in the region of increasing the workload situation and what the pilot can do in those situations. He can fly visual flight situations with limited disturbances and do it with a reason able degree of precision. Beyond that, he's "overed". Therefore, we know where the end point is by this example.

Ron Gerdes: From a pilot's point of view, pilot workload obviously consists of looking for numbers. It's the pilot opinion scale that has been used and it's not only dependent upon the task, but if you'll look at the NASA TN written by Cooper and Harper that goes along with the rating system, you'll note that the word "compensation" comes into play. It's really the amount of compensation that the pilot has to produce to get around the problem of using the control system during the flying task that integrates into workload. When that compensation requirement gets so high that the pilot can no longer perform the task, and you can measure that by his performance, then you've identified a very high workload. I was going to ask Ron Hess if any of his analyses would talk to a measurement of quantifying workload?

Ron Hess: No, as a matter of fact, one of the criticisms of the present prediction scheme that we have is that there's nothing in the performance that you can go to and point at and say that it's workload. O.K. I could probably, given enough time, work my way around workload in that particular context.

LTCOL. Iles: Another way of looking at it would be from an operational point of view; namely, that V/STOL really affords us the potential for flexibility in our operations such as take-off, landing and recovery operations. You immediately define our workload problem if you see standard operating procedures creeping in that detract from the flexibility

of maneuvering associated with the task that you want to do. For example, you know right away in a stepped approach that we've got a workload problem and that we've reached a limit; hence operationally, we're forced into reducing our operational flexibility by changing our task. As soon as you see that, it's a clue right away.

Duane McRuer: There are, Bob, a number of ways in which you can quantify workload very precisely if you will define a task that's also relevant to the measure situation. The way that we've had the most success is the use of the so-called "cross-coupled sub-critical task" in which all tasks are made in one experimental treatment to be saturating completely as far as attentional demands are concerned. Then the increment between that fully saturated situation with the side tasks and the ordinary tasks (which are rated) are then measured and compared. In these instances, it has been demonstrated that the attentional demand on tasks of the kind that Bob's talking about can be precisely measured. It's been done a couple of times. In connection with what Ron said, the Cooper/Harper ratings are correlated directly with the excess control capability or with the attentional demands on a task in that particular same fashion. Now you can't use that test procedure for all tasks, but it happens on hover and transition to a hover, for instance, that there are some experimental data that have been done in that way. So if you don't like pilot ratings, you can go to these other more quantitative measures, if you like. They turn up with exactly the same answer.

Ringland: That's right. Unfortunately I don't have a slide here that shows it, but we have a very neat little curve which correlates all three of those measures, one right on top of the other, for a series of controlled elements. Pilot opinion ratings, attentional demands in a side task and various controlled elements are parameters along the curve. I think it has actually appeared in a number of our reports.

Henry Kelley: In your discussion displays versus flight control simplifications, you implied that we may never be able to fly IFR approaches with V/STOL's unless we have at least attitude stabilization. I'd like to submit that if, in the future, the display becomes improved to be equivalent to the pilot's view out of the window, then we may be able to live with the handling qualities for that task at the current level of operation. It just looks like that to me.

Ringland: My response to that would be: if you could really give the pilot what amounts to a VFR, "real-world" looking out of the cockpit situation, you are putting him in the position that the Harrier pilot is in today. Today he flies VFR with an aircraft which is marginally stable. I would also say, as I think I indicated earlier, that to some degree you cannot get that close to the real world, and you do tunnel his vision down through a heads-up display. Hence, you are going to be in even worse shape in terms of trying to provide that stabilization through the pilot's eyeball. And remember the point that was made earlier; namely, the pilot can't take his eyes off the display, for if he does, he has lost it!

Craig: There is one other point on this curve that I'd like to bring out, and that was an attempt on our part to say that there's a combination of these variables that are going to be combined to relieve the workload to a level that is acceptable; i.e., he can do the mission without compromising the flight profile that he's trying to fly. If we had the total visual world, like in the AV-8, we know that the pilot can do it visually. However, even in that situation, the pilot is saturated -- or he's totally worked. If the total visual world were available to him, he'd still be killing snakes in the cockpit. That is not the type of thing we need for an operationally flexible vehicle.

Ringland: It's not forgiving.

Kelley: However, the AV-8 doesn't have a sophisticated augmentation system.

Craig: Well, consider a helicopter such as the UH-1 or one of the other current helicopters, and place it upon the same curve. Most helicopters flying today have a degree of augmentation superior to the AV-8. Years ago, they learned one thing about helicopters. We first have to have it trimmable; i.e., it has to tend to hold attitude. They put in very clever little circuits to trim the airplane in attitude so if the pilot did let go of the controls (which were basically a lift-type system with a little feel in it), the airplane would still, low frequency wise, maintain its attitude. Now hovering it didn't do too well, because it drifted off. But in the flight regime of conversion, it would maintain attitude and tend to stabilize in flight path using very low frequency, trim-type augmenters. They were basically attitude augmentation systems of very low order. Then they started putting more augmentation in of the rate form, relative to that low frequency trim function that was being provided for the pilot. In a sense, V/STOL aircraft are trying to violate the rules that have been evolving for basic aircraft in addition to the rules that have been evolutionarily developed for helicopters. The first helicopters flying were six to eight type (Cooper/Harper) pilot ratings. If you want to prove that point to yourself, go out and try to fly the little Huey helicopter, which is still of that early vintage. It's a snake killing situation again. Now the pilots learning to fly state that it's a very, very maneuverable vehicle, but it is totally consuming so far as the pilot's activity is concerned.

Ringland: We had a question over here?

CDR Hornblower: Yes, for the benefit of those who were unable to attend the Safety Symposium last year, I would like to take you up on what you said about accidents. You correctly stated that the history wasn't necessarily the same on this side of the Atlantic as in the U.K. But I wish you had gone a bit further because what came out of that meeting was that, although the total accident rate per 10,000 flight hours as of last December was indeed broadly the same, where they were occurring was not. In the Royal Air Force, the emphasis was on accidents which occurred well on into front-line squadron life where they were losing airplanes in the more conventional ways -- instrument flying, weaponery, and so on. They were not happening to the same degree during the, as you have described, vertical phase of flight in the student

phase. Now taking that argument further, which we did in the sessions that then broke up, there were some interesting differences in the sort of student who was going through the program. In the (Royal) Air Force, for instance, everybody volunteers to go to a Harrier squadron. In every case, the number one choice was the Harrier; number two was either the Jaguar or possibly the Hunter; and number three and four were the Bucaneer and Phantom. Whereas over here, it was very much the other way around. First choice, for various reasons, tended to be Phantoms, or equivalently by locations, Yuma and El Toro. You weren't getting the first choice Harrier people. Consequently, you weren't necessarily able to choose the best students to go to the Harrier. Now, to some extent, remarks like the ones you made, tend to foster this reputation which works against the airplane, and that again may be why Marines, on the whole, are not volunteering to go to Harriers. So I don't think that you should say what you did say; namely, that only a test pilot can really cope with the aircraft.

Ringland: Well, obviously you don't have to be a test pilot to fly the Harrier. I think I would agree with that. However, I would also use your remarks to tend to support my argument that you're talking about having to use highly qualified, highly motivated pilots to fly and learn how to fly this airplane. At least that is a contributing factor. Now I haven't even considered the degenerative feedback that's implied by what you're saying, which is that the airplane has a bad reputation. I don't even know that it has a bad reputation in the fleet. Maybe COL Iles might care to comment on it. I really don't know.

CDR Hornblower: I'd like to add that squadron 231, in four or five months of operation on the ship, hasn't lost an aircraft nor come relatively close to it. That may tend to support the fact that it is the students on one side of the Atlantic that are having the problem.

Ringland: It is certainly true that there was only one of those accidents which was a nonstudent flight. The fact is, I think, that it was the first accident on that chart, which was a nonstudent. All the rest of them were training command type accidents.

CDR Hornblower: That was what was said at the meeting, and people like Air Commodore Hair, who is head of flight safety in the U.K., came across specifically to make these points. Hence I think they're quite worthwhile.

Ringland: I think they're valid points to make. I also feel that the workload is pretty high for that aircraft.

William Hindson: As regards to the configuration scheduling proposition which basically refers to programmable path and nozzle control through the decellerating transition, I'd be concerned with the fact of overly complicating the control system and airframe response at the intermediate thrust-vector angles. Now with respect to mission requirements, the approach and landing task is the major decellerating transition requirement for these kinds of aircraft. It seems to me that that can be fairly well proceduralized without impacting severely on mission capabilities. For example, the procedures that are already being used on the Harrier. And so it seems to

me that it makes sense to try to exploit the situation of going from the case where you have the thrust-vector-angle basically horizontal (a typical airplane) to the case where you have the thrust-vector-angle basically vertical. There you find uncoupled responses, within limitations. Once you get your thrust-vector-angle basically vertical, provided you have a measure of control power for maneuvering while positioning for landing, you may still have satisfactory performance without having to go to the extra cost of incorporating a highly sophisticated flight control system. For example, an exemplary case that deals with problems where you have thrust-vector-angle flying is the Boeing AMST wherein a triple redundant flight control system is used. I think Jack Franklin has shown another example as well in the augmentor wing work at Ames. So I wonder if we need to be as complex as you're proposing. Let's put it another way. The compromise being that, providing we can go from the case where you have a horizontal thrust vector to the vertical thrust vector, we can measure control power and expect reasonable handling qualities based on conventional aircraft. We may be able to save considerable cost and expense.

Robert Flynn: Let me just comment on that. Number one, when we talk about control system complexity, I think Charlie Abrams hit upon the point. Today, it's not the implementation of the control laws that hangs you up. The F-18, for example, has quite a capable digital computer on board. The Boeing YC-14 also employs, as you stated, a triplex digital computer, an older machine that's not comparable to the F-18. Secondly, we're away from the analog computer days, where control system complexity really cost us in terms of circuitry, in terms of trying to match redundant channels, and probably most of all, in terms of preflight checkout of analog circuitry and having to introduce additional dedicated circuitry just to accomplish the checkout status. So I really think that the problem in complexities in the future will go back to the sensors. That technology evolves rather more slowly, in my opinion. Even then, there are major breakthroughs right on the horizon, such as in the form of a strapdown package where you obtain inertial data, all the needed body axis data, and maybe out of the same computation package, your air data.

I think we're overplaying this complexity problem, and what we've seen here in this last paper is really going behind the workload question with a whole new basic philosophy. For years, airplane design, control system design and airplane dynamics has considered the problem of pilot abuse. Protect the airplane against pilot mistakes, pilot abusive maneuvers and things like conservatism in Vmcg giving good stall characteristics, Vmu characteristics, feet on the floor response to engine out...all these kinds of things which we do to protect the airplane and the pilot against mistakes. Now in the V/STOL area, the trend has been just the opposite for a number of reasons, and I think it's not surprising when you view it in terms of accident rates.

Charles Abrams: I'd like to comment a little further relative to Bob Flynn's remarks. I certainly agree with what he says plus the added comment that the requirements for control system complexity are not dictated by performance. They are dictated by reliability, survivability and maintainability. You may get similar performance simply by using a high authority, command augmentation system rather than going through a triplex digital

flight control system. The differences here are that the requirements for survivability dictate the redundancy levels. Also, when you consider maintainability, you're looking for systems with a built-in test and diagnostic capability. This is what dictates control system redundancy.

Ringland: I think Charlie's points are very well taken. It is a whole complex of requirements that dictate a flight control system which appears to be quite complex because of the required redundancy in built-in test features. The automated scheduling demands that we're discussing here are only a portion of the overall requirements that a system like that would have to satisfy. Sam.

Craig: The point that you should have spotted from those curves is that I could pretty well have selected a relatively simple scheduling without duly compromising the vehicle's performance. In fact, to some degree, the CL-84 and the XC-142 incorporated a compromise schedule for pilot configuration management relief in order to keep the workload up. The point is that perhaps they didn't go far enough, but they did relieve the pilot of a great deal of configuration management by tying things together.

Gerdes: I guess I'm jealous since I didn't see the X-14 up there on your list. It's been flying 20 years, and although some of you may not be aware it has a digital flight control system. It once was pointed out to me, "No, it's not really digital because it has a manual backup". Well, it is really "fly-by-wire", including taking off, landing, and hovering very nicely by "fly-by-wire". There is an IBM single thread computer in it. We have a built-in test feature which takes about one minute to go through. Of all the problems that we've had with the airplane, none of them has been associated with the digital flight control system. The problems have always been something else. It's a very simple airplane with a very sophisticated digital computer onboard. It not only can "fly-by-wire", but it has a model following system which is programmable and includes variable stability. We've had very little difficulty with the digital system, therefore in my mind, that is a good item. As a pilot, I think that digital "fly-by-wire" is an excellent way to go for VTOL.

Craig: Please accept my apologies, Ron, for omitting your airplane from the chart.

Ron Hess: Before we have the fourth paper in this session, COL Iles has asked if he can present a slide pertinent to the last discussion.

LTCOL Iles: Gentlemen, I would like to make sure that we all keep proper perspective while looking at accident statistics and include the overall system. That system is made up of a logistics loop and a training loop, and those two loops will affect the stability margin for the complete system. If you have either logistics or training problems, those factors will influence the pilot's ability to be workload tolerant. Logistics problems will impact upon the amount of flight time available to the pilot to be current and up to speed for handling the task. Another point arises if we have training problems. Our whole system within the U.S. Navy and Marine Corps starts back in the training command where the pilots

obtain their first principles of flight, which is explained to them during the first phase of learning. Right now that doesn't include V/STOL principles. That training phase is passed along to the operational units. It used to be that they received their first principles in the training command with a conventional rotary-wing aircraft and then moved along into an operational unit where they obtained an introduction to a particular model. They're really in the second phase of learning there when they receive their insight into how to operate that machine. Well, that whole process has to swing and move together so that he (the pilot) is progressing along an individual learning curve to achieve the ability to handle the workload of the task. The whole system has to be considered. Now we're talking about a system that's new and unique to our services, hence it's not back yet into our first level of training. This doesn't detract from the statement that, "Yes, we have a workload problem". That's very true, but we must consider these system effects at the same time. Thank you.

RATIONALE FOR SELECTION OF A FLIGHT CONTROL SYSTEM FOR LIFT CRUISE FAN V/STOL AIRCRAFT

ROMAN K. KONSEWICZ

MCDONNELL AIRCRAFT COMPANY

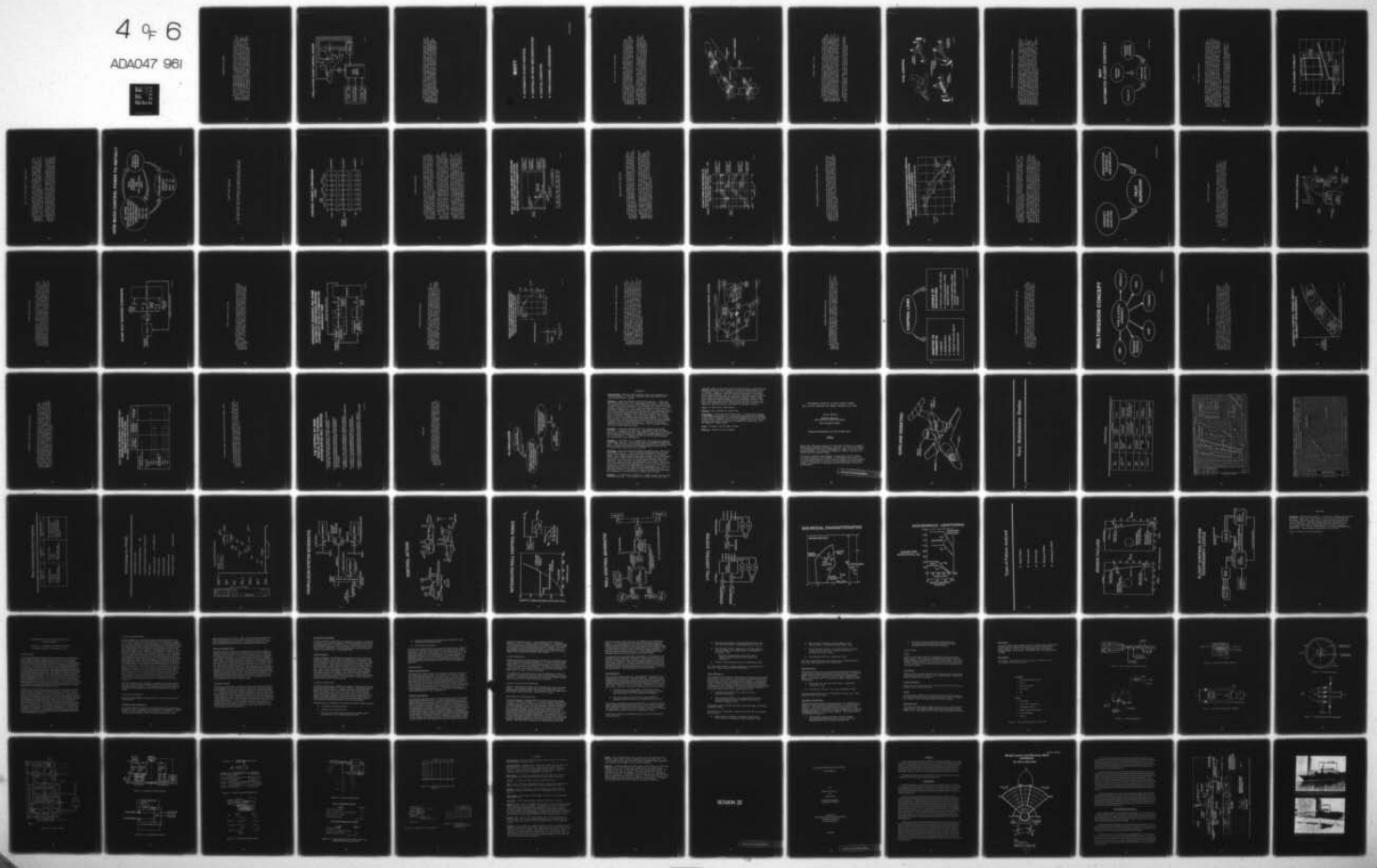
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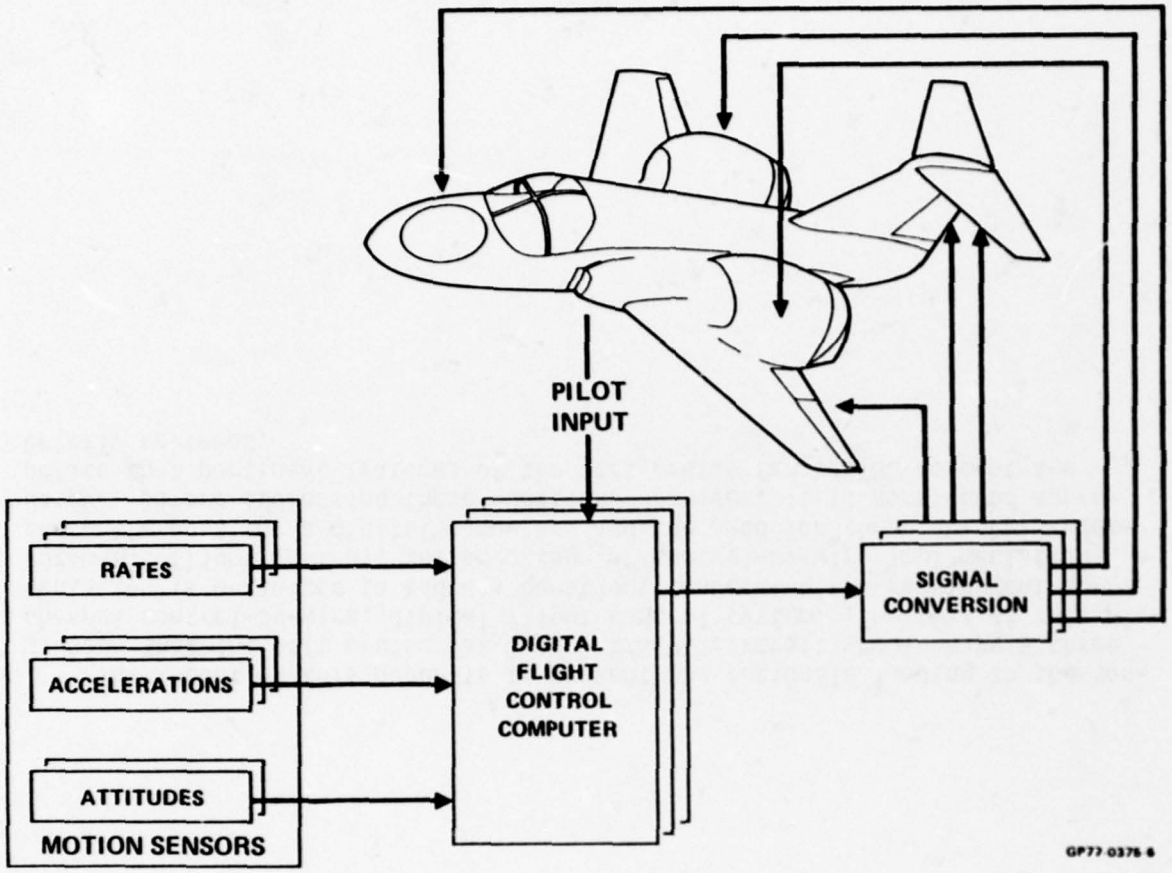
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INTRODUCTION AND SUMMARY

The Type A V/STOL concept is an approach to broaden the Navy's air capabilities in performance of a variety of offensive, defensive, and utility missions. This concept's effectiveness lies in its ability to operate from small ships in adverse weather, low visibility, and rough sea conditions. This role can be effectively filled by a lift cruise fan aircraft designed with a highly capable, flexible, and reliable flight control system. These qualifications rationally suggest a digital control-by-wire flight control system. The system is triplicated for flight safety and mission performance reliability, with redundancy management implemented using comparison and in-line monitoring techniques for failure detection and isolation.

TYPE A V/STOL FLIGHT CONTROL SYSTEM



The intent of this paper is to present the rationale leading to the conclusion that the lift cruise fan Type A V/STOL aircraft should have a three channel control-by-wire, digital flight control system. The text of this presentation is organized to address questions concerning the requirement for automatic flight control, the advantage of control-by-wire implementation, the preference for a digital computer, and the need for three channel redundancy. Before addressing these questions, however, it is considered appropriate that pertinent features of the lift cruise fan V/STOL concept are briefly reviewed.

WHY?

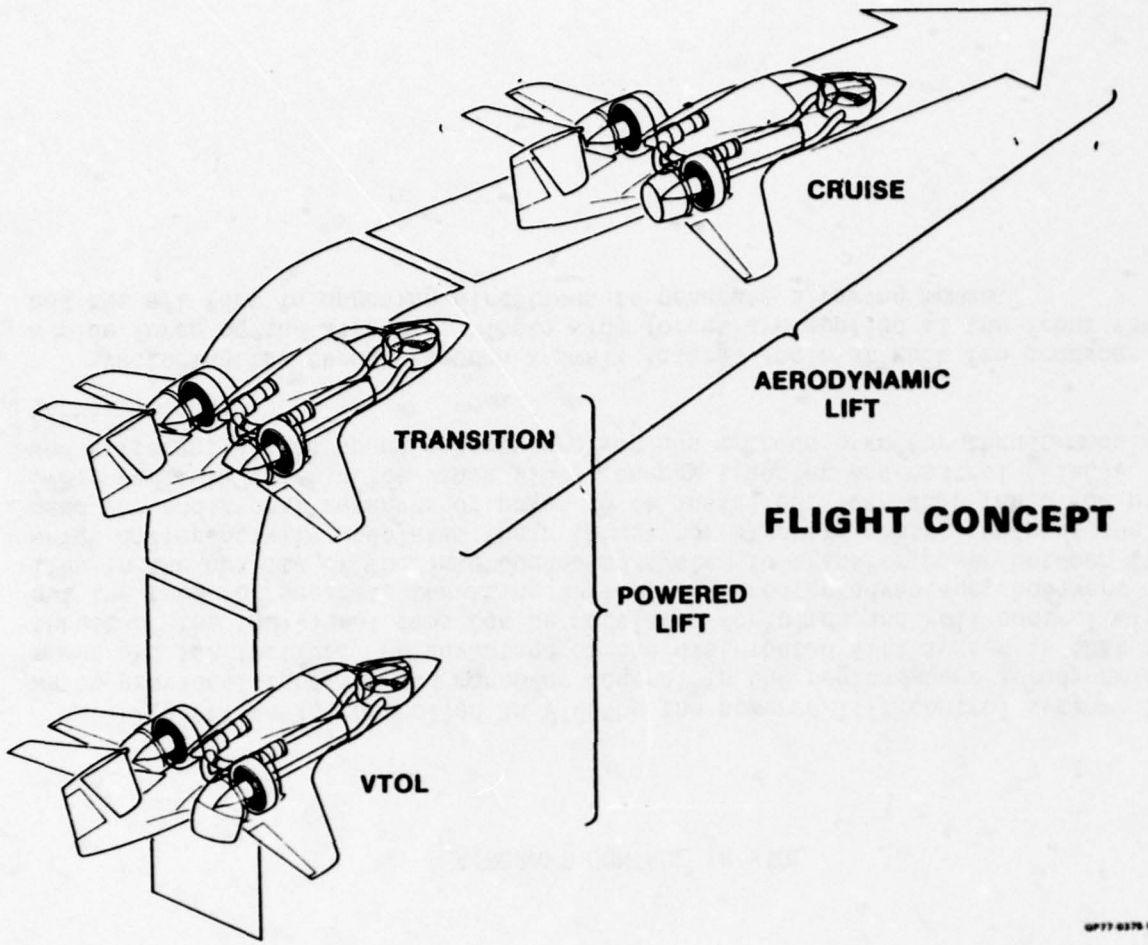
- AUTOMATIC FLIGHT CONTROL
- CONTROL-BY-WIRE IMPLEMENTATION
- DIGITAL COMPUTER
- THREE CHANNEL REDUNDANCY

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THE LIFT CRUISE FAN V/STOL CONCEPT

Results of past engineering studies have shown that the lift cruise fan concept possesses attractive performance capabilities for a variety of V/STOL missions. The concept is configured around a propulsion system consisting of engines and fans which are interconnected for power transfer to maintain aircraft moment balance following an engine failure in flight. The power transfer system uses gas ducting in the turbotip fan application and shafts and gears in the mechanical fan concept.

The fundamental principle of any V/STOL flight concept is the capability to use and combine direct propulsive thrust with aerodynamic lift for the purpose of extending the conventional flight envelope to include pure vertical takeoff and landing performance. Both powered lift and aerodynamic lift are needed to perform the transition maneuver. Transition is accomplished by vectoring the thrust either by means of a flow directing nozzle or by tilting the whole nacelle.



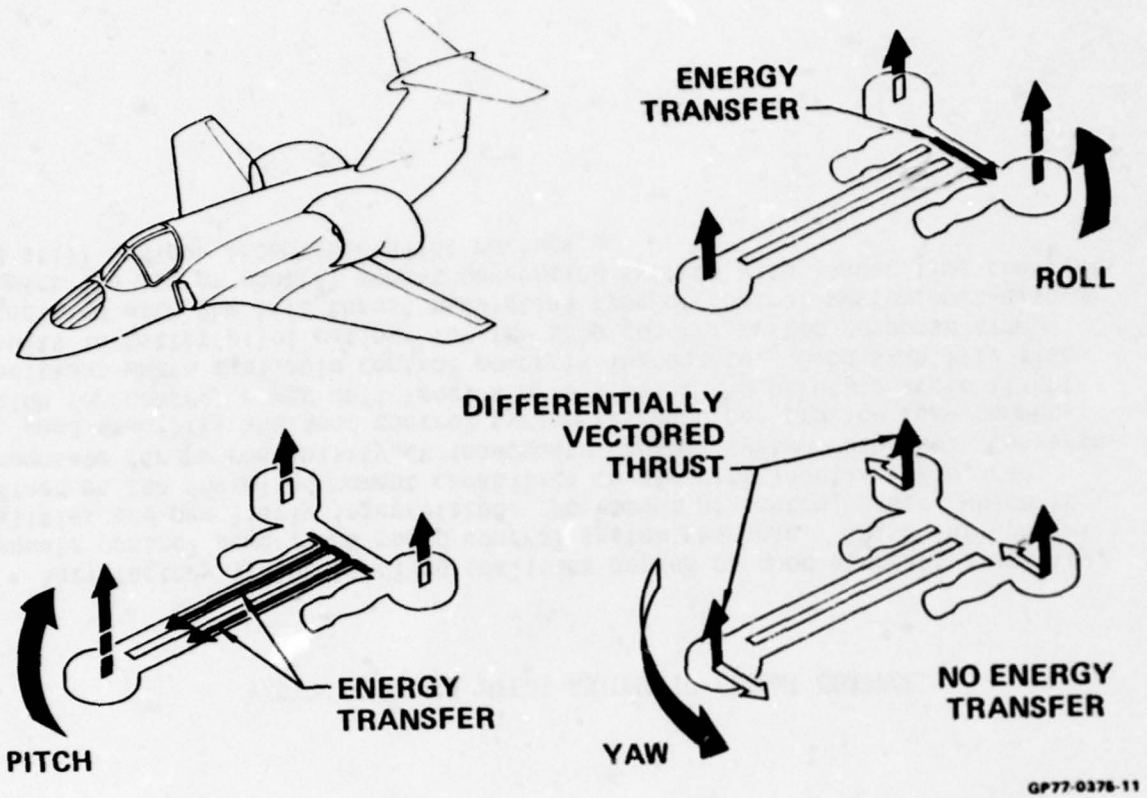
FLIGHT CONCEPT

AIRCRAFT CONTROL IN VTOL

The airplane is controlled in VTOL by the powered lift control system which provides stability and maneuver control in the region where aerodynamic means are ineffective. An advantage of the distributed lift system is that the thrust of the individual fans can be modulated for pitch and roll control without the need for separate thrusting devices. A greater advantage, however, lies in the ability of the interconnected system to transfer power between fans which differentially modulates their thrust for aircraft control without the need for additional reserves of power to be installed. Variable fan blade pitch (VP), variable inlet guide vanes (IGV), energy transfer and control (ETaC), and differential fan speed changes are various methods used for thrust modulation.

Vectoring the thrust through a small lateral angle at each fan produces a side force on the aircraft. These side forces are applied at the front fan and the aft fans in opposing directions to generate a yawing moment.

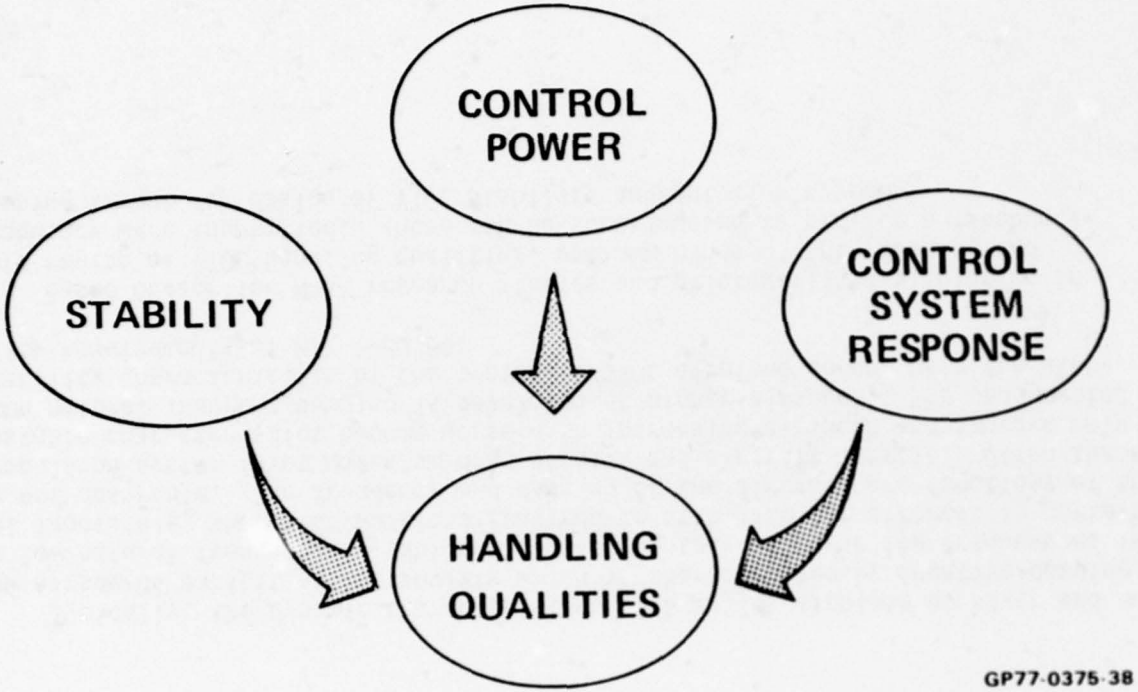
VTOL CONTROL



V/STOL AIRPLANE NEEDS AUTOMATIC FLIGHT CONTROL

Satisfactory V/STOL handling qualities depend on good aircraft stability, adequate control power, and rapid control system response. These influential qualities are peculiarly interrelated. No amount of control power, which is defined as the installed moment capability to aircraft inertia ratio, can compensate for poor stability or inadequate control system response. Conversely, good stability and good control system response can provide some compensation for control power deficiencies by assisting the pilot to avoid flight conditions where available control power is inadequate. Good stability also results in better pilot ratings for the same control system response time associated with the lift thrust modulating type of control system. It also permits the use of control moment generating systems with longer time constants and still achieve acceptable pilot ratings.

WHY
AUTOMATIC FLIGHT CONTROL?



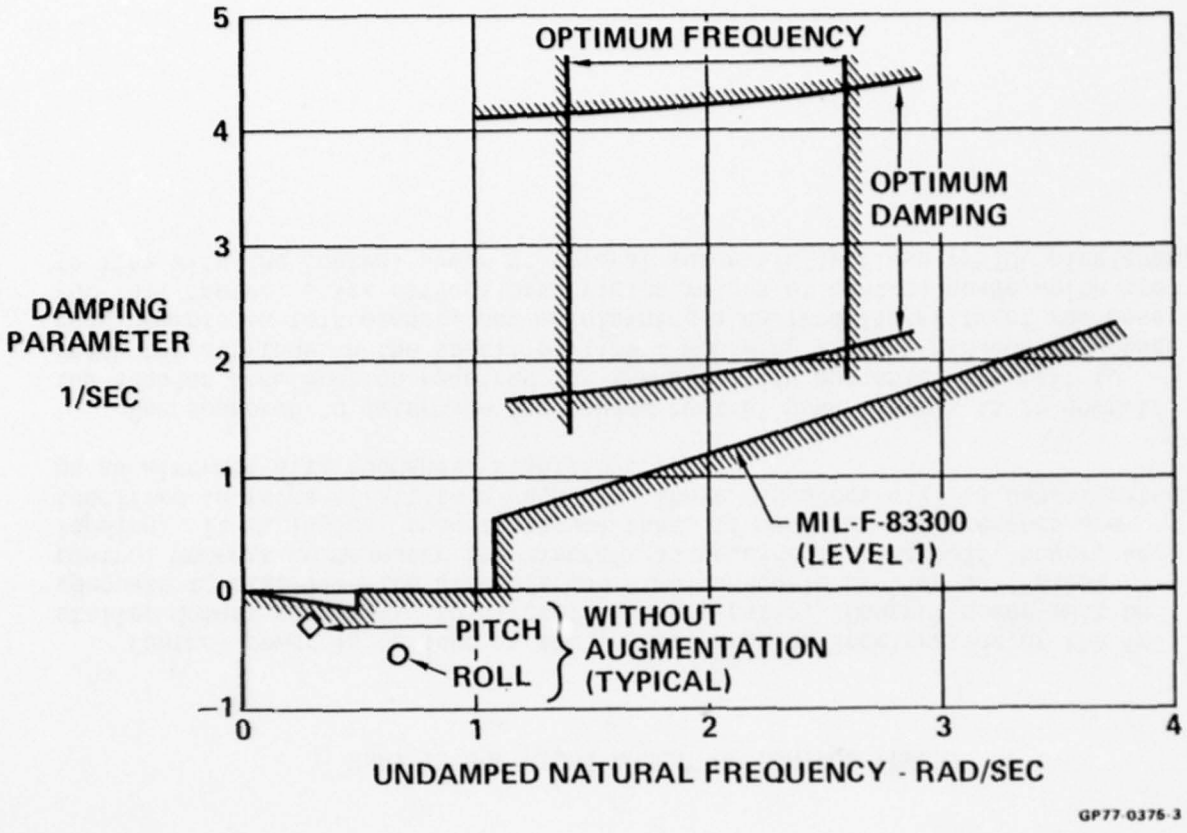
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V/STOL AIRCRAFT STABILITY

Typically, the dynamic characteristics of a V/STOL airplane at hover and low airspeeds exhibit an instability which is characterized by negative damping at low natural frequencies. While the piloting task at these low frequencies is not impossible, the pilot workload required to stabilize the aircraft is certainly not desirable. The frequency and damping of the aircraft are functions of the propulsion system inlet momentum drag effects and aircraft inertia. Often these unstable characteristics become worse with increasing airspeed and improve only when natural inherent damping is developed at higher airspeed. The unaugmented stability characteristics of the typical V/STOL airplane do not meet the stability requirements of MIL-F-83300.

Based on earlier NASA research studies and piloted flight simulation in this region of VTOL handling qualities, optimum bands of both damping and frequency were identified. These can be superimposed to provide a frequency-damping target for design of VTOL stability augmentation systems.

VTOL DYNAMIC STABILITY

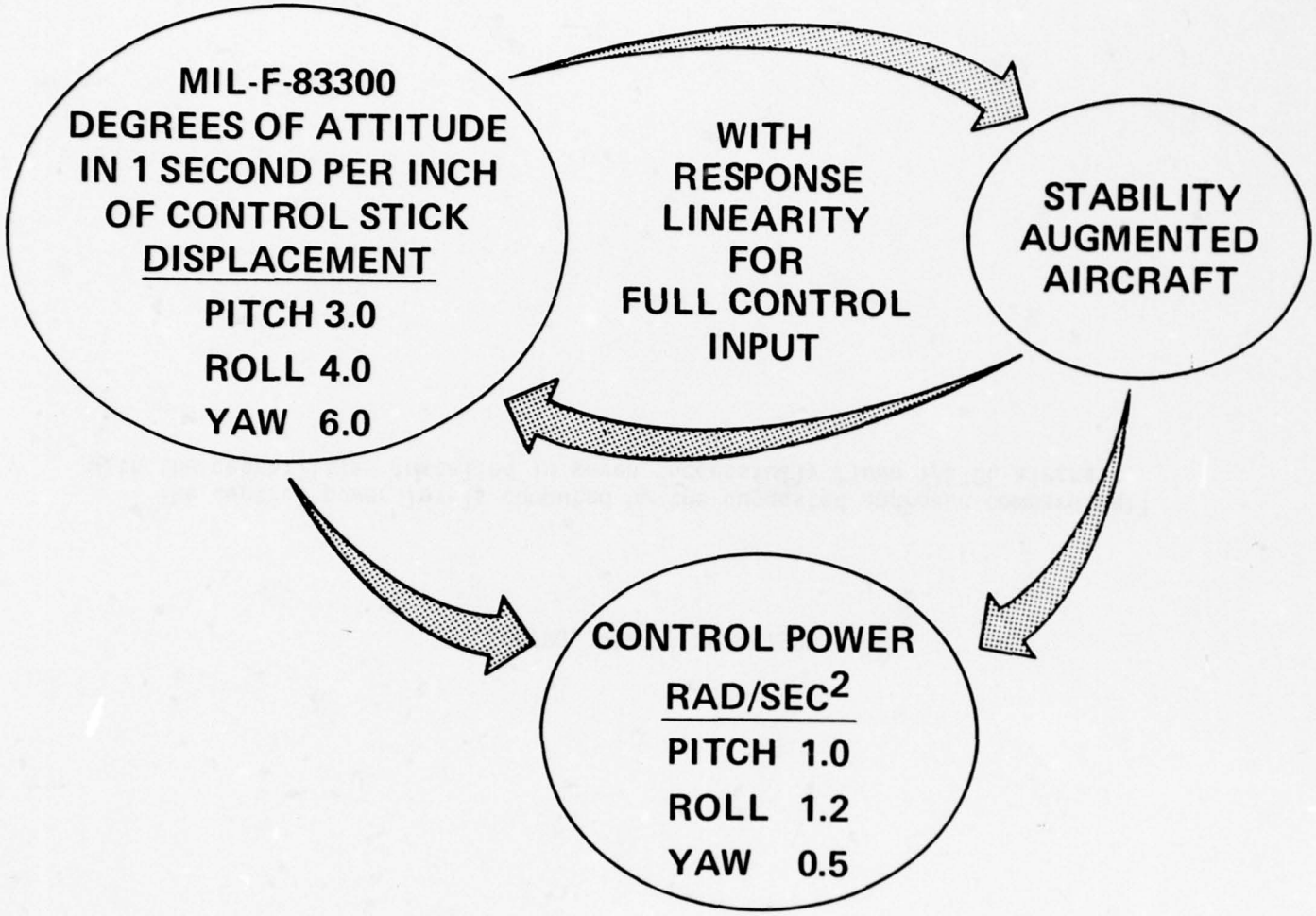


WHAT IS THE RIGHT AMOUNT OF CONTROL POWER?

Control power is defined as the initial angular acceleration or the installed moment capability to aircraft inertia ratio. Control power must be adequate to stabilize the aircraft and simultaneously provide sufficient control moments to maneuver the aircraft as required for takeoff, hover, and landing. It is logical then to assume that, if maneuver requirements are specified in terms of attitude response, these maneuvers will be demonstrated on an aircraft with augmented stability.

One approach to determine the needed control power levels is to compute the angular acceleration required for the stability augmented aircraft to reach the attitude in the specified time. Applying the MIL-F-83300 response requirements in this manner, and maintaining a desired linearity of response for full control stick deflections, yields values of control power which are in line with the control power of several successfully flown V/STOL airplanes.

HOW MUCH CONTROL POWER TO INSTALL?

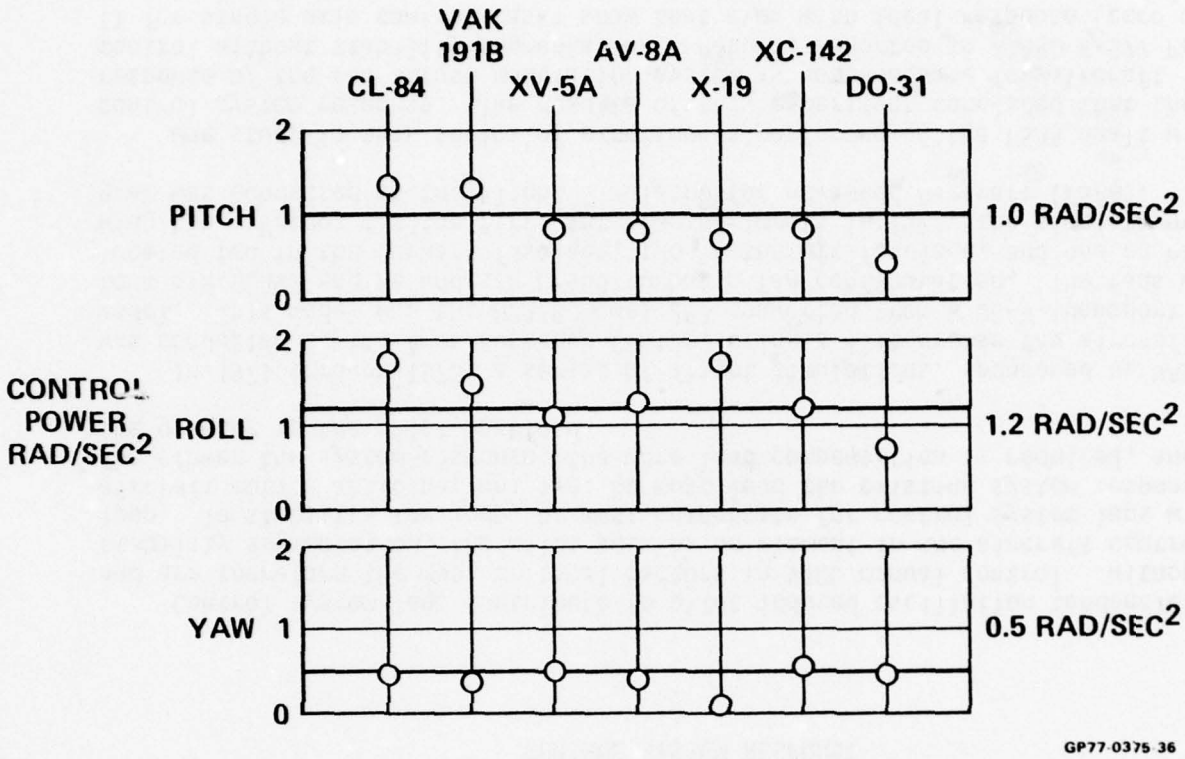


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CONTROL POWER COMPARISON

The control power levels computed by the suggested approach compare well with the capabilities installed in seven successfully flown V/STOL aircraft.

CONTROL POWER COMPARISON
HOVER



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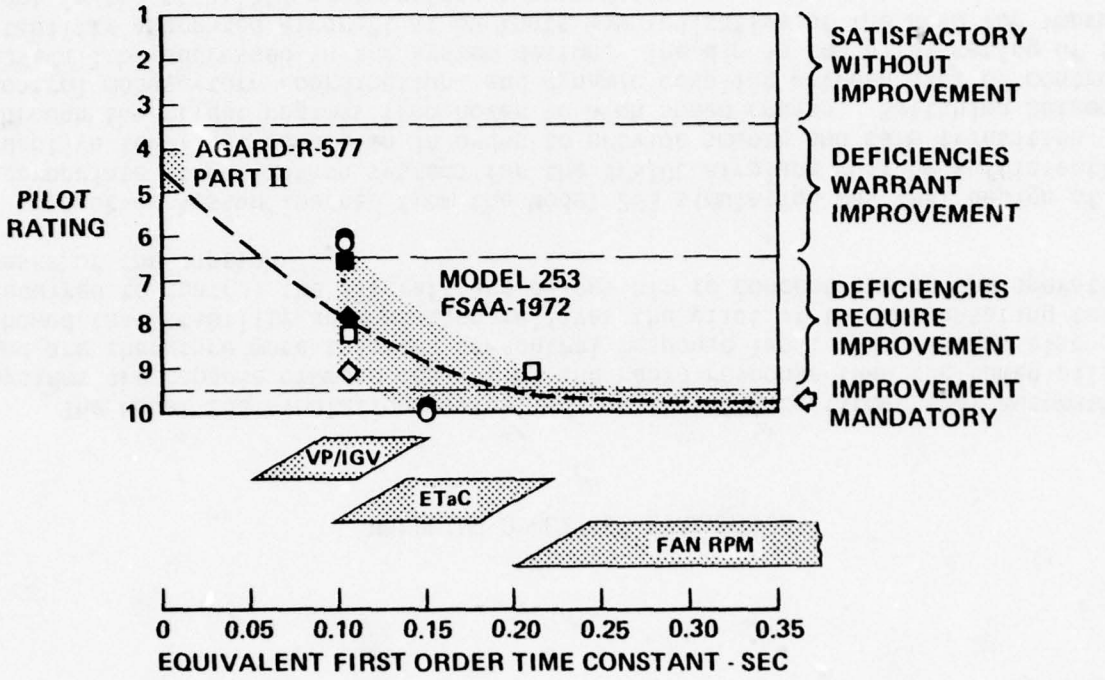
CONTROL SYSTEM RESPONSE

Control system lags contribute to pilot induced oscillation tendencies and are therefore the most critical factors in VTOL manual control. Without stability augmentation, the pilot acts as an element in the aircraft control loop. To stabilize the loop, he must compensate for control system lags with aircraft motion anticipation; i.e. he must lead the existing system response. The slower the system response, the more lead compensation is required, and the greater is the pilot workload.

In 1971 through 1973, a series of flight simulations, sponsored by NASA, was conducted at the Ames Research Center, using a lift cruise fan aircraft model. This model was the MCAIR Model 253 converted from a DC-9 transport to a six GEJ97 engine and six LF460 turbotip fan configuration. The fans were located two in the forward fuselage, two in the aft fuselage, and one on each wing tip. Except for the first set of experiments in 1971, the simulation program was conducted on the Flight Simulator for Advanced Aircraft (FSAA).

One study in this series of experiments performed on the FSAA dealt with control system response. The results of this experiment concluded that the response of the fan thrust modulation system is not adequate for aircraft control without stability augmentation. Results reported in AGARD-R-577 Part II for single axis control tasks show that even with ideal response (zero control lag) the pilot rating remains unsatisfactory (PR 4 to 5). Conversely, with attitude stability augmentation and a control moment time constant of 0.22 second in the Model 253, pilot ratings are satisfactory.

EFFECT OF CONTROL MOMENT RESPONSE ON AIRCRAFT HANDLING QUALITIES WITHOUT STABILITY AUGMENTATION



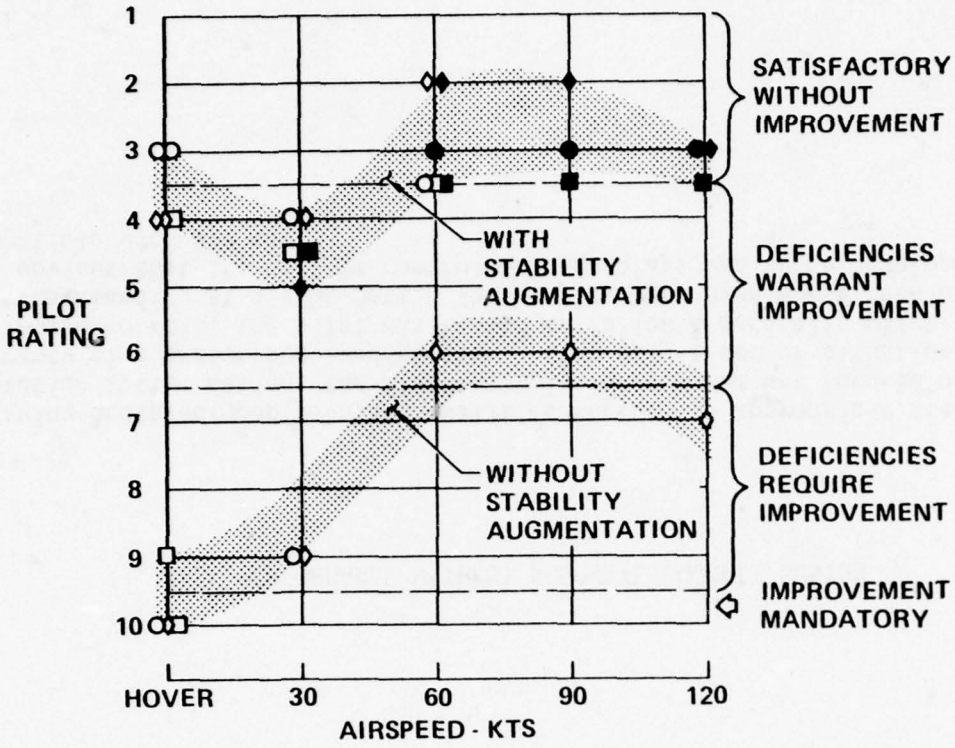
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HANDLING QUALITIES EVALUATION

The Model 253 simulation evaluations on the FSAA confirmed that automatic systems are capable of more consistent and rapid response than the human pilot, and are therefore more tolerant of control response lags. The results also showed that stability augmentation relieves the pilot of the compensating tasks required to control the aircraft and allows him to concentrate on the operational tasks of the mission.

Another lesson learned from the Model 253 simulation was that design of the appropriate stabilization systems for the V/STOL airplane must be sufficiently adaptive to flight condition in order to provide smooth and safe transition through the flight regimes from hover to high speed cruise. Switching between control modes, turn coordination, and dynamic coupling between axes of control must all be addressed in the system design. The dip in the pilot rating of the stability augmented aircraft at 30 knots was indicative of the need for improvement in the stability augmentation system design.

FLIGHT SIMULATION RESULTS
EVALUATION OF HANDLING QUALITIES
MODEL 253 LIFT CRUISE FAN AIRCRAFT - FSAA - 1972
TIME CONSTANT = 0.22 SEC



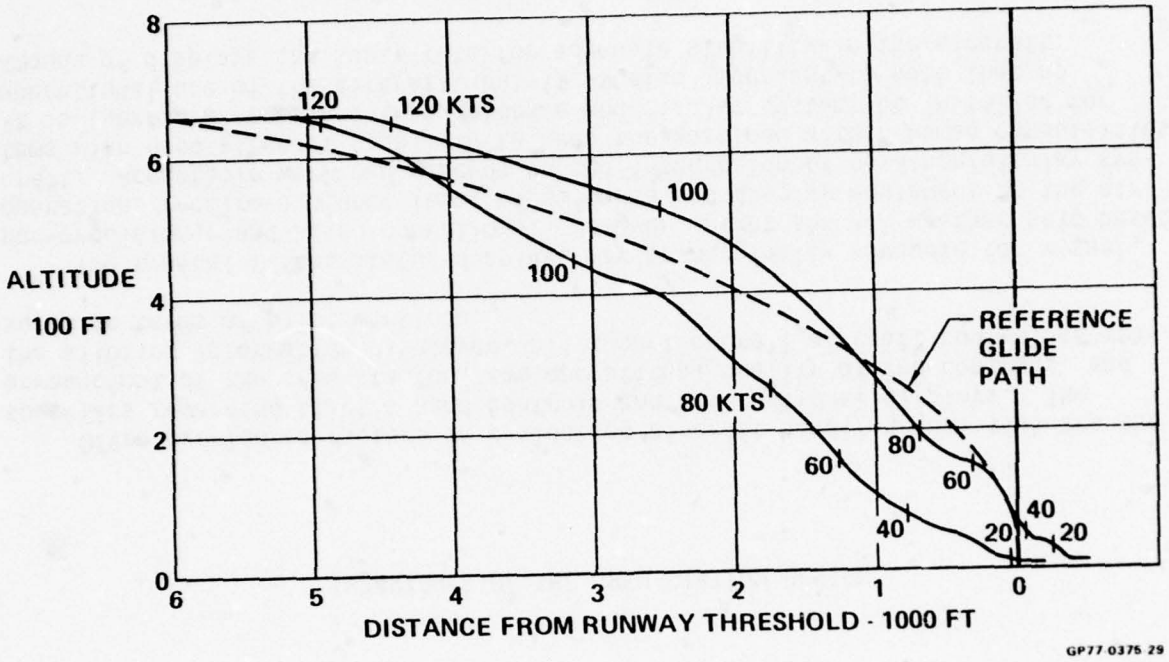
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TASK PERFORMANCE WITHOUT ADEQUATE COCKPIT DESIGN

Having achieved good handling qualities through an appropriate stability augmentation system design, the flight simulation program was focused on the performance of a prescribed landing task. With only a set of situation displays in the cockpit, the pilot was tasked to follow a parabolic glide path to vertical landing at a VTOL port. The results were even worse than expected. It was obvious that the cockpit controls and displays had to be developed to be compatible with the task.

SIMULATED CURVED PATH APPROACHES TO VERTICAL LANDING WITH STABILITY AUGMENTATION BUT INADEQUATE GUIDANCE

FROM MODEL 253-FSAA-1972 SIMULATION RESULTS

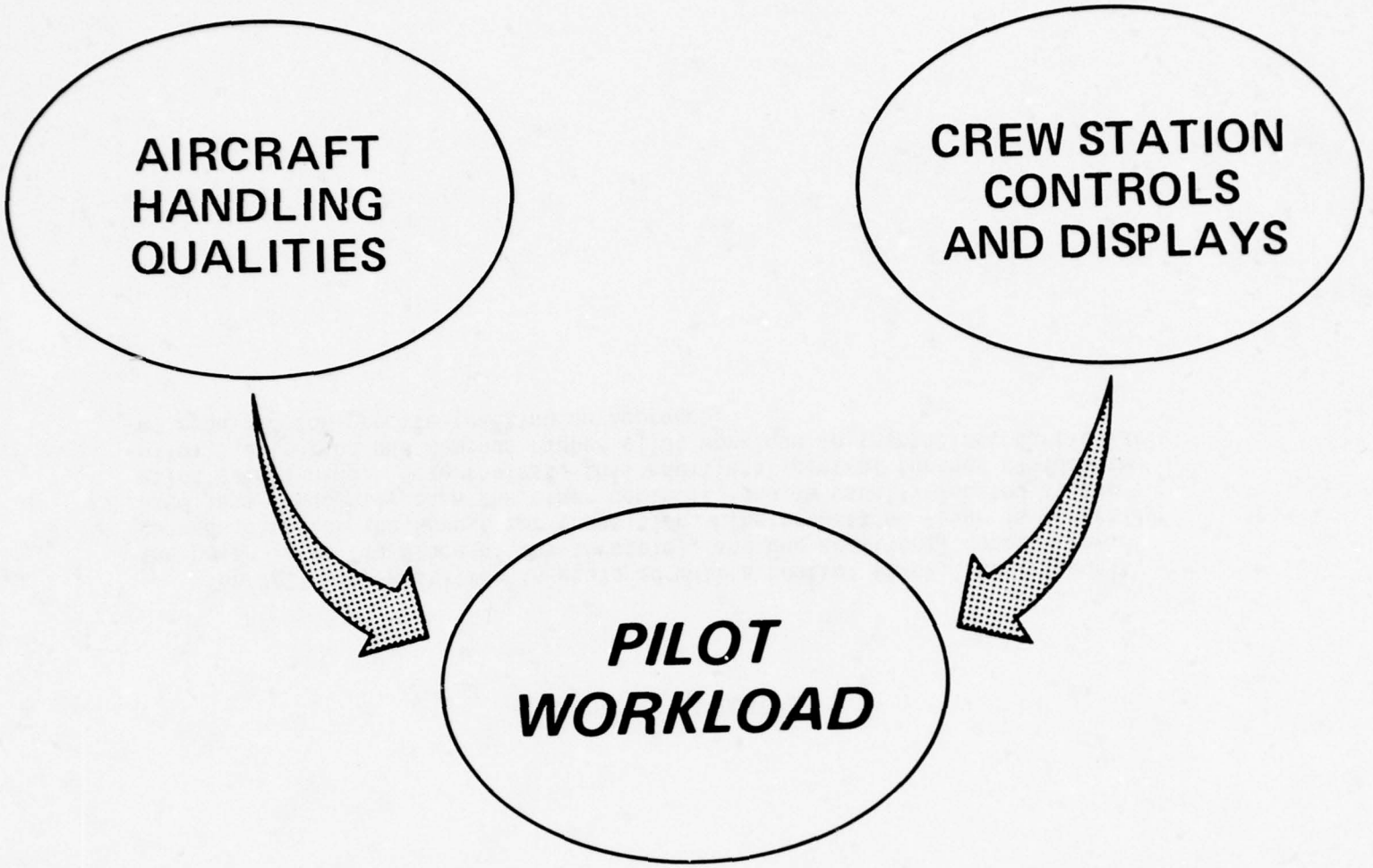


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IMPORTANCE OF THE CREW STATION DESIGN

Often overlooked factors in evaluating aircraft handling qualities are the specifics regarding pilot's hand controls and informational displays. The arrangement of the crew station, the operational quality of the controls, and the piloting information displayed, all impact overall aircraft control as measured in terms of pilot workload.

The typical flight status displays may be marginally adequate for visual, non-precision, land based operations. However, night and all weather ship based operations require a higher level of guidance and display equipment in the aircraft. Acceptable workload depends on the integration of guidance/display systems with good aircraft stability to keep the workload within human capabilities. It is therefore necessary that guidance and display systems be installed for operational use of the aircraft, but it is also important to note that no amount of displays can substitute for adequate stability in the aircraft.

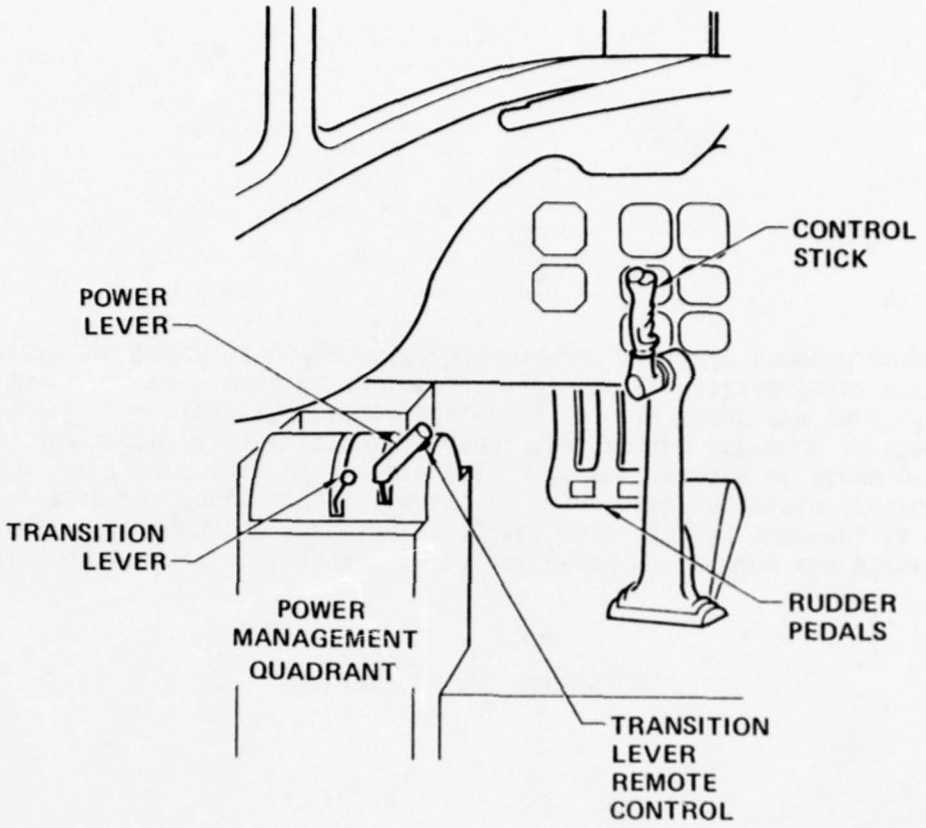

AIRCRAFT HANDLING QUALITIES
CREW STATION CONTROLS AND DISPLAYS
PILOT WORKLOAD

GP77-0375-37

V/STOL COCKPIT CONTROLS

The V/STOL crew station is equipped with a control stick, rudder pedals, the power lever (in place of the throttle), and one additional control required to vector the thrust for transition. The transition lever is generally used less frequently than the other controls, and is usually located at the pilot's left hand. Nevertheless, this additional control further divides the pilot's attention and demands higher pilot workload in transition, particularly as required for precise tracking on approach.

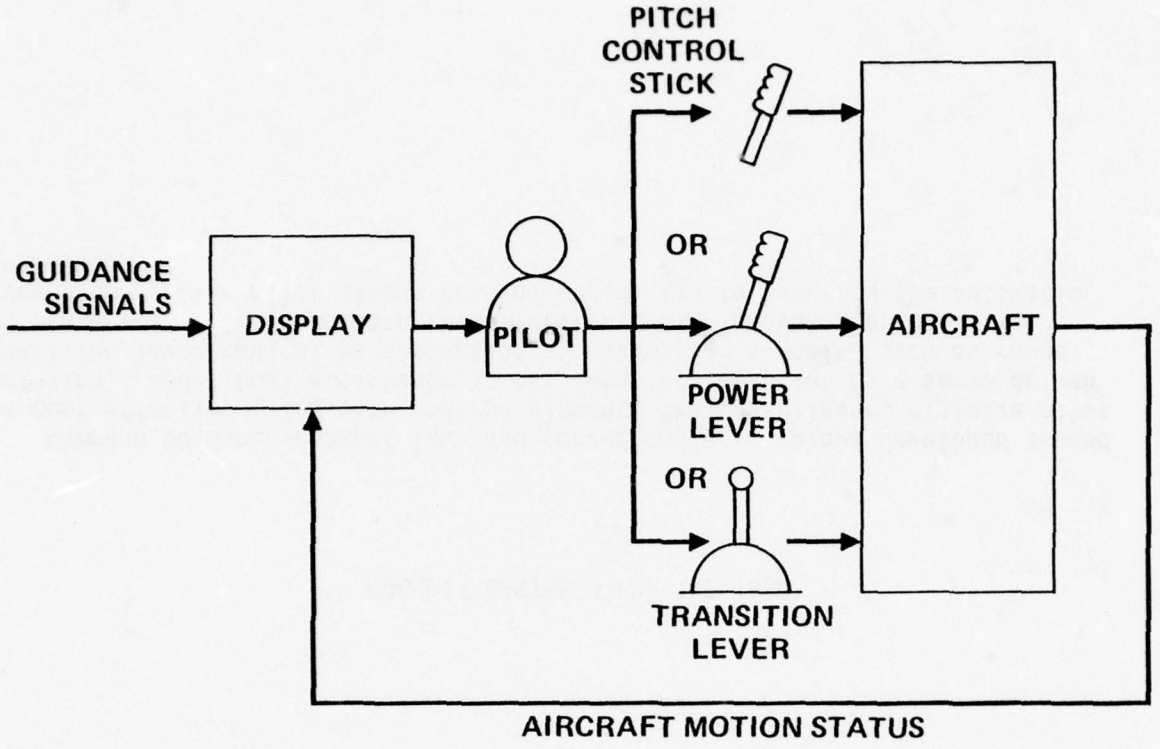
CREW STATION CONTROLS



COCKPIT CONTROL CONFUSION

Tracking of a localizer signal can be performed by banking the aircraft in the conventional manner. Tracking the glide path signal, however, is more difficult because the power lever, transition lever, and the pitch control stick affect the flight path of the aircraft. In performance of steep or curved path approaches to a vertical landing, the landing approach is the transition maneuver. To track the glide path, particularly under IFR conditions, deceleration on approach must be performed using the transition lever with certain precision, which is quite difficult without suitable command guidance.

GLIDE PATH TRACKING CONFUSION

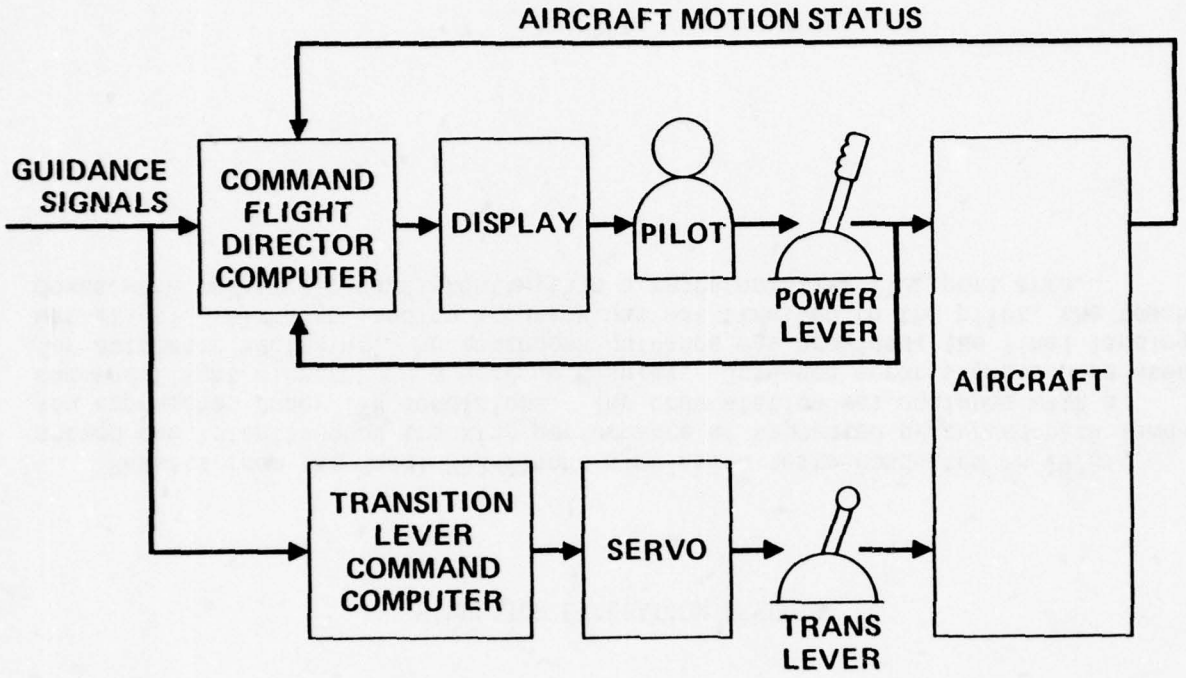


GP77-0375-18

COCKPIT DESIGNED FOR THE TASK

Command guidance control laws and corresponding displays developed around the most effective glide path control element, the power lever, minimize pilot confusion. Additional assistance is provided for the pilot by a servo driven transition lever control as a function of navigation signals, such as range and range rate. The automatic thrust vector control moves the transition lever slowly. The pilot always retains capability to override the automatic servo loop.

APPROPRIATE GUIDANCE AND SOME AUTOMATIC ASSISTANCE PROVIDE CAPABILITY TO DO A COMPLEX IFR APPROACH TASK



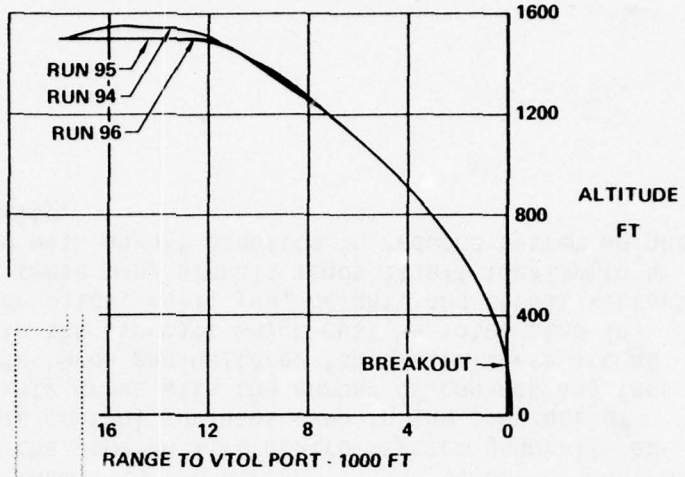
SIMULATOR EVALUATION RESULTS

Results from the Model 253 flight simulation tests conducted in 1973 showed consistently good tracking performance of segmented or curved path landing approaches under IFR conditions. The crew station was equipped with a command flight director on a head up display. Guidance error signals were used for automatic vectoring. No touchdown guidance was provided; the final landing was visual. Although landing accuracy was not stressed to the pilot, the touchdowns were relatively consistent within a representative VTOL port area.

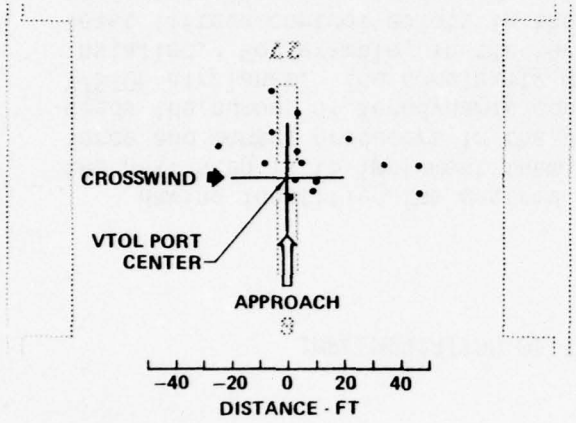
SIMULATED IFR CURVED PATH APPROACHES TO VERTICAL LANDING WITH COMMAND FLIGHT DIRECTOR AND AUTOMATIC VECTORING

FROM MODEL 253-FSAA-1973 SIMULATION TESTS

CURVED PATH APPROACHES



TOUCHDOWN DISPERSION

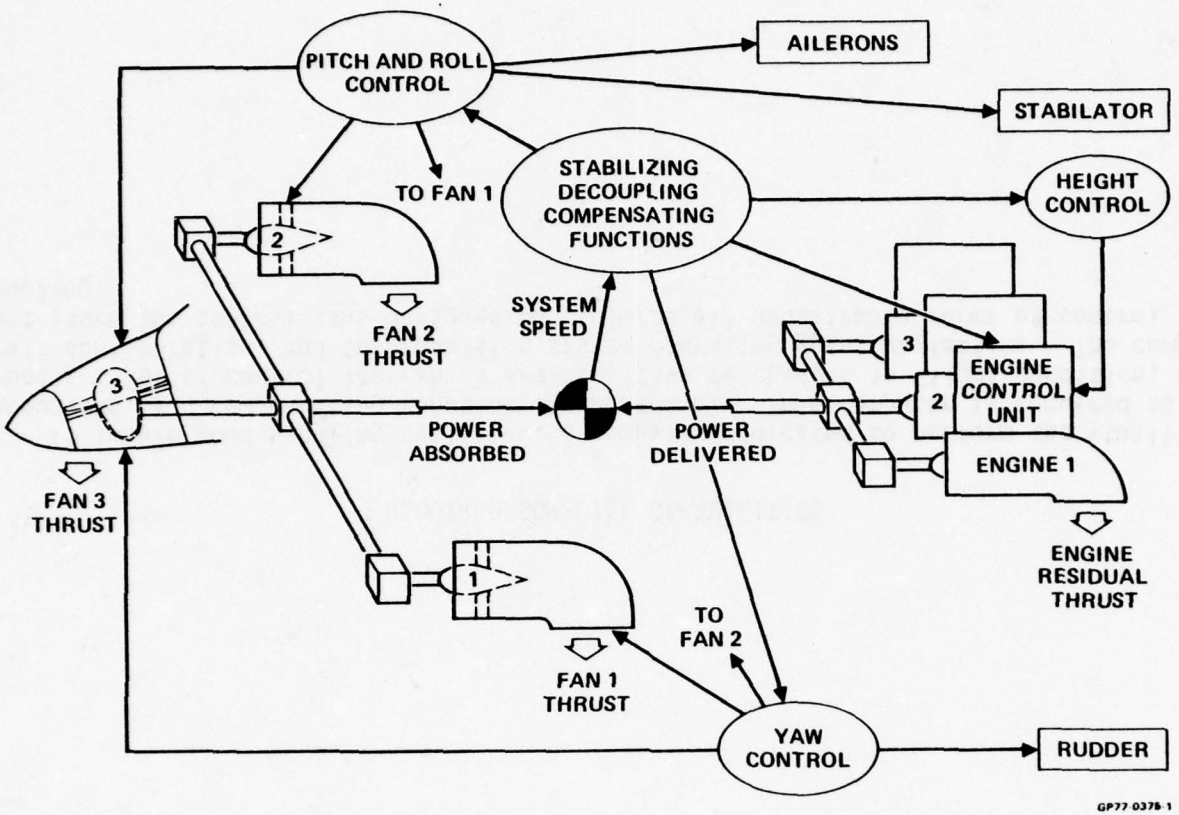


GP77 0376 26

IMPLEMENTATION OF THE FLIGHT CONTROL SYSTEM FUNCTIONS

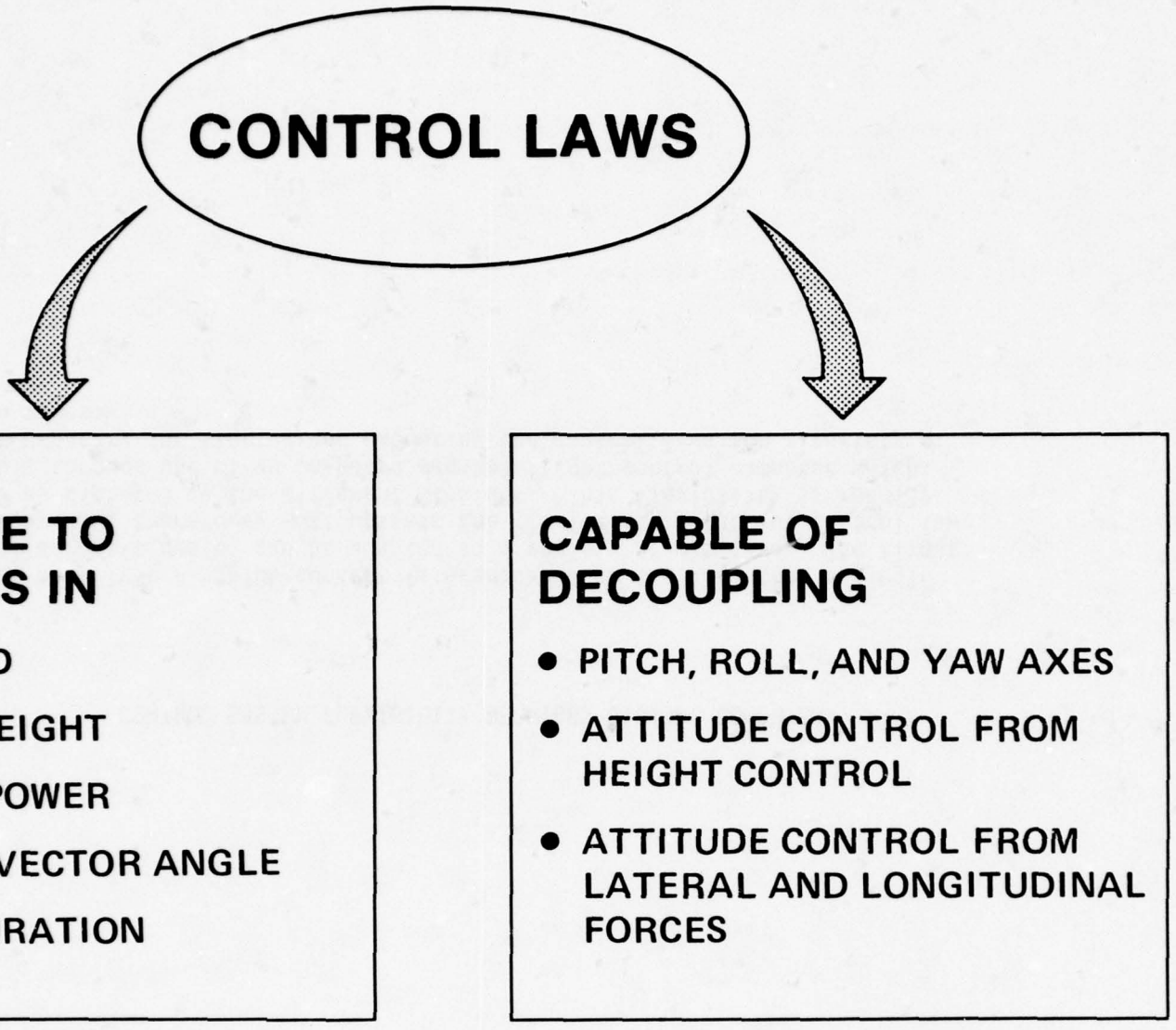
Having identified the desired functions of the flight control system, the next step is to implement them into the aircraft. The number of control force and moment producers in the powered lift control system generally exceeds the number of aerodynamic control surfaces even in the simplest of V/STOL airplanes. The complexity grows with the number of engines and fans installed. For example, in the three engine/three fan system there are at least fifteen control points in the aircraft which must be integrated in various combinations to provide pitch, roll, yaw, height, and thrust vectoring control. The distribution of these many signals lends itself ideally to a control-by-wire implementation with payoff benefits in reduced system weight, volume, and mechanical complexity.

INTEGRATED PROPULSION/FLIGHT CONTROL SYSTEM



REQUIRED COMPUTER CAPABILITIES

To insure good handling qualities, a computer dedicated to perform the stabilizing, decoupling, and compensating functions is essential. This computer is required to process a set of control laws which are sensitive to changes in flight condition, aircraft configuration, and to propulsion system operating point variations. The computer must store the control laws designed to minimize all undesirable forms of control coupling.

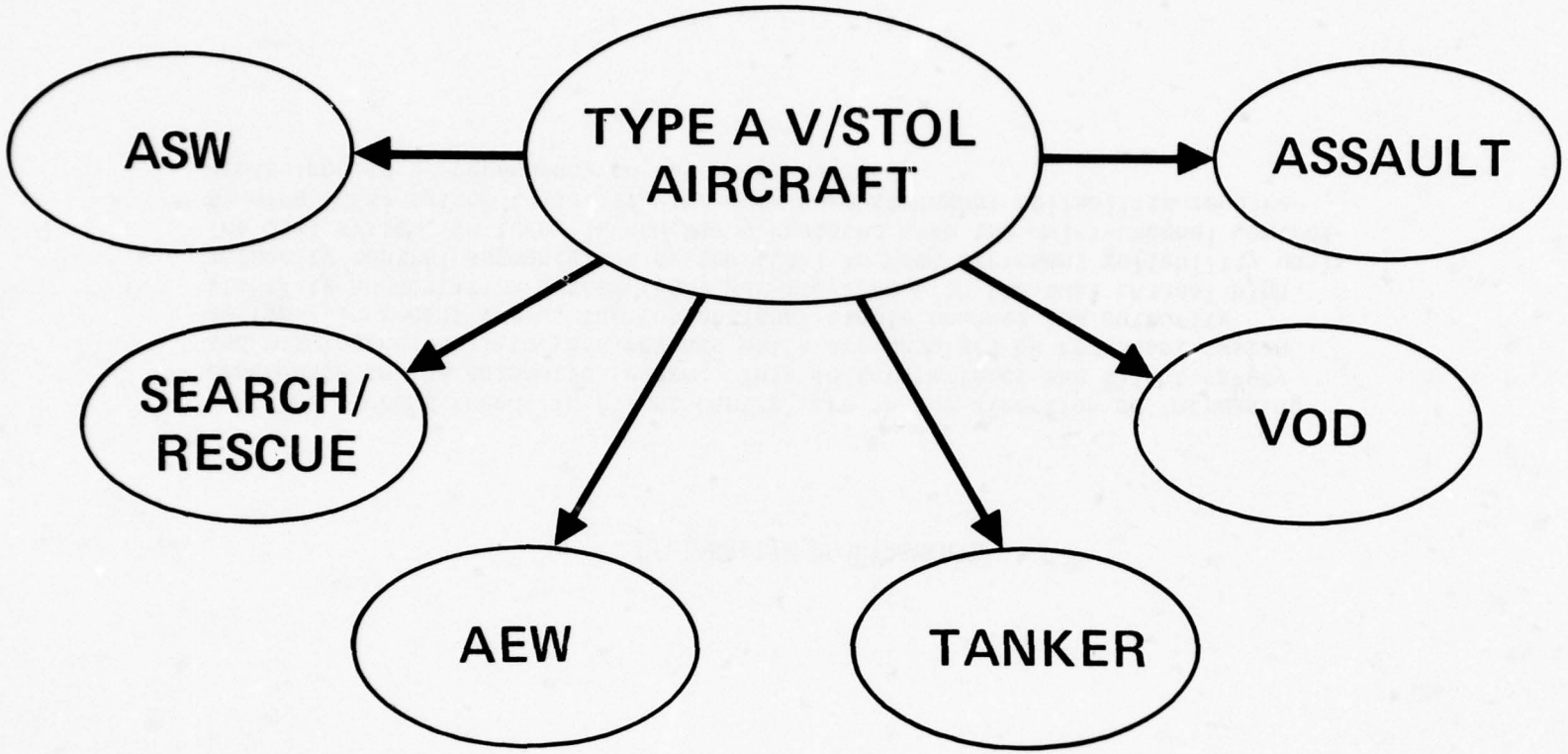

CONTROL LAWS
ADAPTIVE TO CHANGES IN
• AIRSPEED
• GROSS WEIGHT
• ENGINE POWER
• THRUST VECTOR ANGLE
• CONFIGURATION
CAPABLE OF DECOUPLING
• PITCH, ROLL, AND YAW AXES
• ATTITUDE CONTROL FROM HEIGHT CONTROL
• ATTITUDE CONTROL FROM LATERAL AND LONGITUDINAL FORCES

GP77-0375-20

CONTROL SYSTEM FLEXIBILITY REQUIRES DIGITAL COMPUTER

The Navy Type A V/STOL concept is predicated on the idea that a single baseline aircraft design can be adapted to a variety of missions. The flight control system, therefore, must possess the flexibility to accept control law changes as dictated by the different missions. This flexibility is readily available through use of an on-board digital flight control computer which has the capacity for storing and executing the control laws for a variety of mission modes.

MULTIMISSION CONCEPT

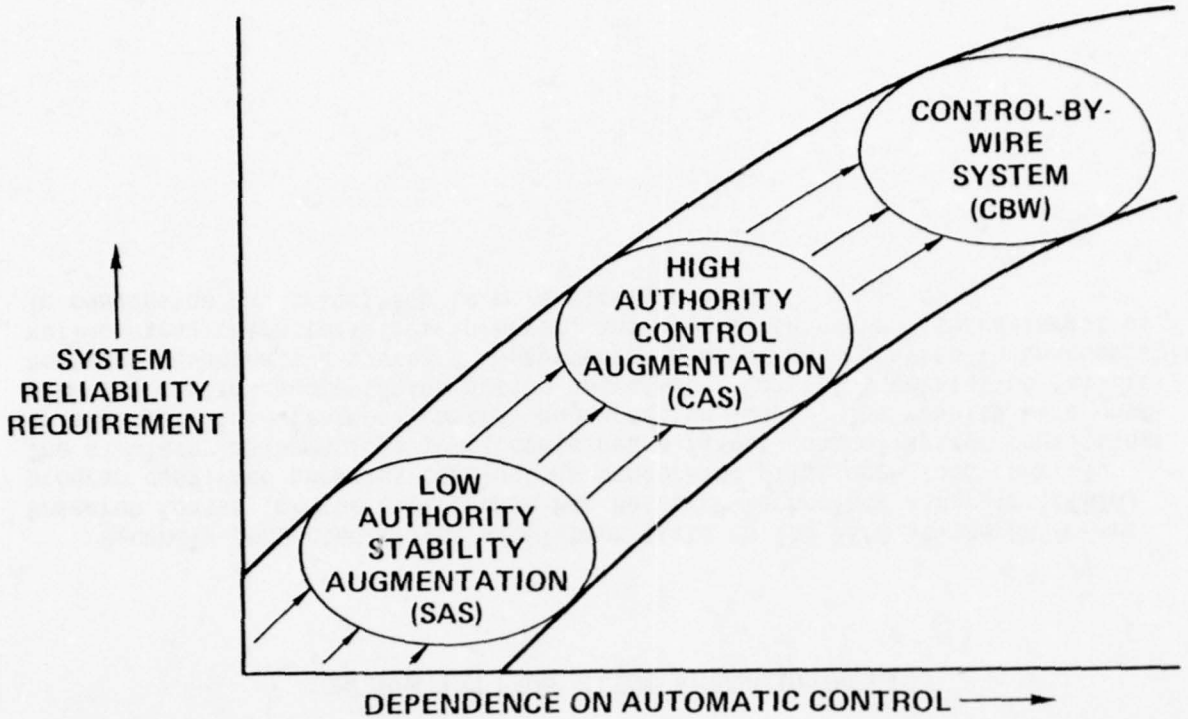


GP77-0375-13

RELIABILITY REQUIREMENTS

The current trends in flight control are in the direction of increasing dependence on the automatic system. This in turn affects the flight safety and mission reliability requirements which are resolved by redundant system design. In recent years, the conventional single channel low authority stability augmentation system (SAS) was replaced with the dual channel high authority control augmentation system (CAS) to meet stringent reliability goals. The dual system, in turn, is now being replaced with the multi-channel control-by-wire (CBW) system to satisfy the even more stringent reliability requirements imposed by dependency on automatic control.

AUTOMATIC CONTROL TRENDS IMPACT RELIABILITY REQUIREMENTS



CONFIRMATION FROM RECENT SIMULATION RESULTS

Recently conducted flight simulation tests on the FSAA at the NASA Ames Research Center for the Lift Cruise Fan Research Technology Aircraft (LFRTA) program confirmed previous conclusions concerning pilot open loop control. The simulator mathematical model contained a flight control system consisting of a direct link with dual control augmentation loops. The results were good with the control augmentation system operating. Control augmentation failures, however, reverted the system to unaugmented control and resulted in unacceptable roll control characteristics in hover, and poor pitch control characteristics in conversion and transition to a vertical landing.

LIFT/CRUISE FAN RESEARCH TECHNOLOGY AIRCRAFT WITH DUAL CONTROL AUGMENTATION SYSTEM

SEPTEMBER 1976 FSAA SIMULATION RESULTS

	SATISFACTORY WITHOUT IMPROVEMENT	ADEQUATE PERFORMANCE/ WORKLOAD TOLERABLE	IMPROVEMENT REQUIRED
CAS OPERATING			
COMPOSITE RATING	X		
CAS FAILED			
HOVER			
ROLL			X
PITCH		X	
YAW		X	
TRANSITION AND CONVERSION			
ROLL		X	
PITCH			X
YAW		X	

GP77-0375-17

THE THREE CHANNEL CONTROL-BY-WIRE DIGITAL FLIGHT CONTROL SYSTEM

The continuing development of digital technology, such as effective and reliable inline monitoring techniques, provides the basis for the three channel control-by-wire digital flight control system. Such a system provides the necessary capabilities for the Type A V/STOL application while meeting the dedired mission reliability and flight safety goals.

THE CONTROL-BY-WIRE DIGITAL FLIGHT CONTROL SYSTEM (DFCS) WILL PROVIDE

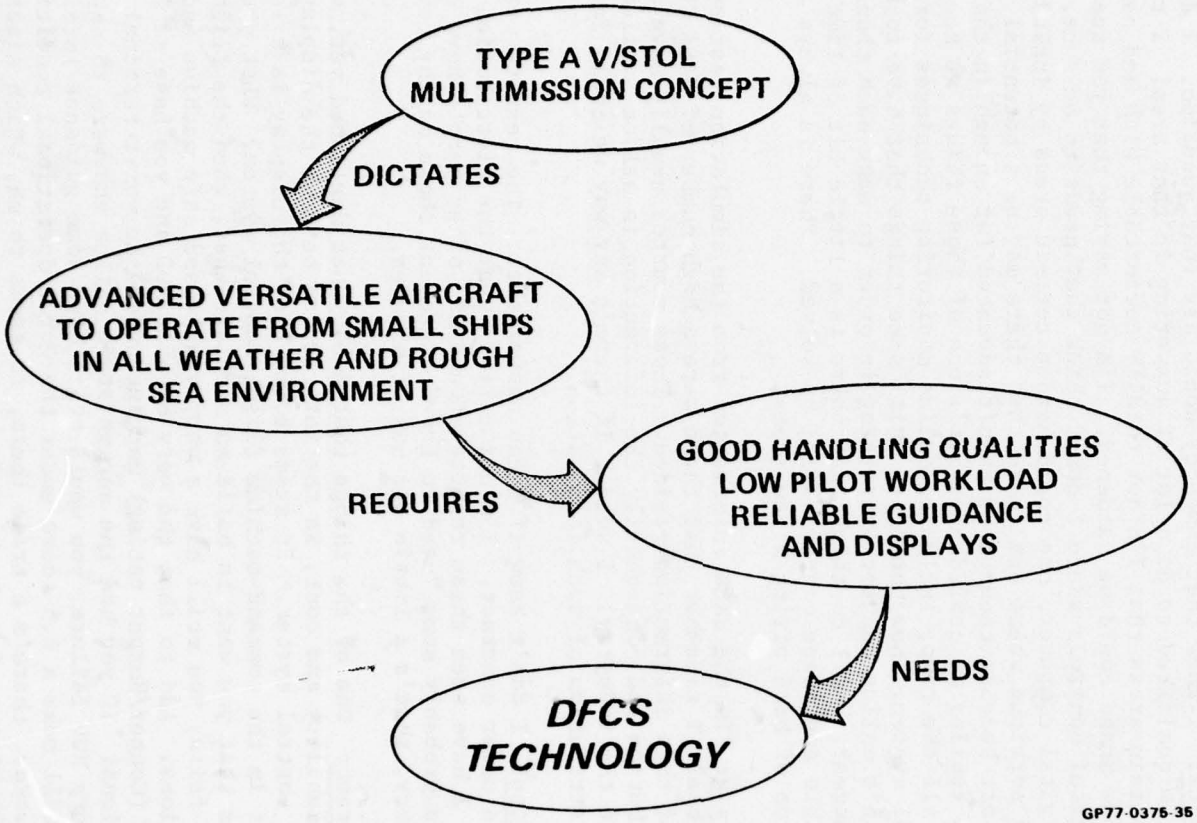
- EFFICIENT IMPLEMENTATION OF CONTROL LAWS FOR HOVER, TRANSITION, AND CONVENTIONAL FLIGHT REGIMES
- EFFECTIVE BLENDING OF CONTROL LAWS FOR SMOOTH TRANSITION BETWEEN AERODYNAMIC AND POWERED LIFT FLIGHT
- CAPABILITY FOR V/STOL APPROACH TO SHIPS THROUGH AUTOMATED FLIGHT-PATH CONTROL AND TASK-ORIENTED DISPLAYS
- FLEXIBILITY OF PROGRAMMING CONTROL LAWS FOR DIFFERENT MISSIONS AND AIRCRAFT CHARACTERISTICS
- CAPABILITY FOR RECONFIGURATION OF CONTROL LAWS TO CORRECT OR COMPENSATE PROPULSION/CONTROL SYSTEM FAILURES

GP77-0375-27

CONCLUSION

The Type A V/STOL multimission concept requires an advanced versatile aircraft which can operate from small ships under adverse weather and rough sea conditions. Such an aircraft must possess good handling qualities, low pilot workload and reliable guidance and display systems. These features can be provided by a suitably designed control-by-wire, digital flight control system.

IN CONCLUSION . . .



DISCUSSION

Charles Abrams: There has been no mention made in your presentation of the backup system. Do you feel comfortable today when flying an all-visual system without a backup?

Konsewicz: I knew that somebody would ask that question. I don't know that I'm qualified to do a lot of answering in that area. I think there are certain areas that I'm not totally comfortable with and certainly some of those areas could be hardened. I'm not saying that you need to include mechanical controls since I don't think that needs to be done. But in the digital computer, one could harden certain areas by including, possibly, analog portions where one feels that there may be a potential problem of this sort because technology hadn't advanced far enough in that area to give a feeling of confidence. It's one of those things we keep talking about all the time, including online monitoring techniques for a triplex digital system. Now there are still some things that have to be developed. You can't online monitor everything in order to make each channel totally independent, but I do think that there is a little bit of time still available and these concerns will be solved. There is always a fallback position of hard wiring a few items.

Sam Craig: Is the data information from the simulation test readily available? I remember that there were a high number of NASA CR's where most of this information resided. Those sources usually have a very limited distribution and consequently the information is seldom available to the rest of the industry. I wonder if there's any way we could facilitate the distribution of such information.

Konsewicz: I don't know if I can answer that. The results were submitted to NASA under contract. I'm not certain what the distribution limitations were. I have seen these reports around and other people have obtained them. There's probably some "need to know" statement shown on the cover, but I'm sorry, that's a little bit out of my area.

Dave Green: One of the things that nobody has mentioned yet, with respect to reliability and cost, is the interaction between the display and the flight control system. It seems to me that the display is a redundant element in the command-machine flight control system. What you have really said is that you want to build an aircraft that, when the flight control system fails, you still have a very viable and safe machine under VFR conditions. Add to that the very capable HUD and you have at least a 5.5 to 6.5 (Cooper/Harper rating) machine under the worst terminal operational conditions. If you had the augmentation online and were to experience a primary HUD failure, you would still have some guidance left. You could then still make a 6.5 score under the worst operational conditions. In other words, there's a trade there, it seems to me, which sizes and shapes the reliability of both the HUD and the flight control system.

Konsewicz: I'll take that in the form of a comment since I'm not sure that a question was posed. I don't think I'm at a point to really get into a

discussion except to say that we have been talking about a system where the handling quality was never a question. I'm not even talking about 5.5 or 6.0 ratings. Instead, I'm talking about going all out with the control-by-wire type technology. There's no point in regressing to a very high pilot workload situation, even in a so-called level three flight condition. We're talking about providing the capability to sustain a major failure such as losing a complete channel, and still performing a mission. Then we go further than that and consider the event that when you lose two of them you're sufficiently safe to bring the vehicle back to the ship under almost any conditions that you could expect to encounter normally.

Green: But that's with a good display.

Konsewicz: Yes, obviously you require that.

Duane McRuer: Let me just add to Dave's point. I think that your design is fundamentally good since it is based upon having a gracefully degrading system, with the capability that the graceful degradation can proceed along as many paths as possible. Since it is a fundamental that all of us would naturally agree upon, it really hasn't stressed us all that much. It's the essence of a simple design.

Green: You seem to have the right solution.

Konsewicz: Thank you for your comments.

PRELIMINARY DESIGN OF A FLIGHT CONTROL SYSTEM FOR A V/STOL AIRPLANE WITH GEARED VARIABLE PITCH FANS

Philip Gotlieb

Technical Specialist
Boeing Military Airplane Development

Boeing Aerospace Company

Manuscript unavailable at the time of publication.

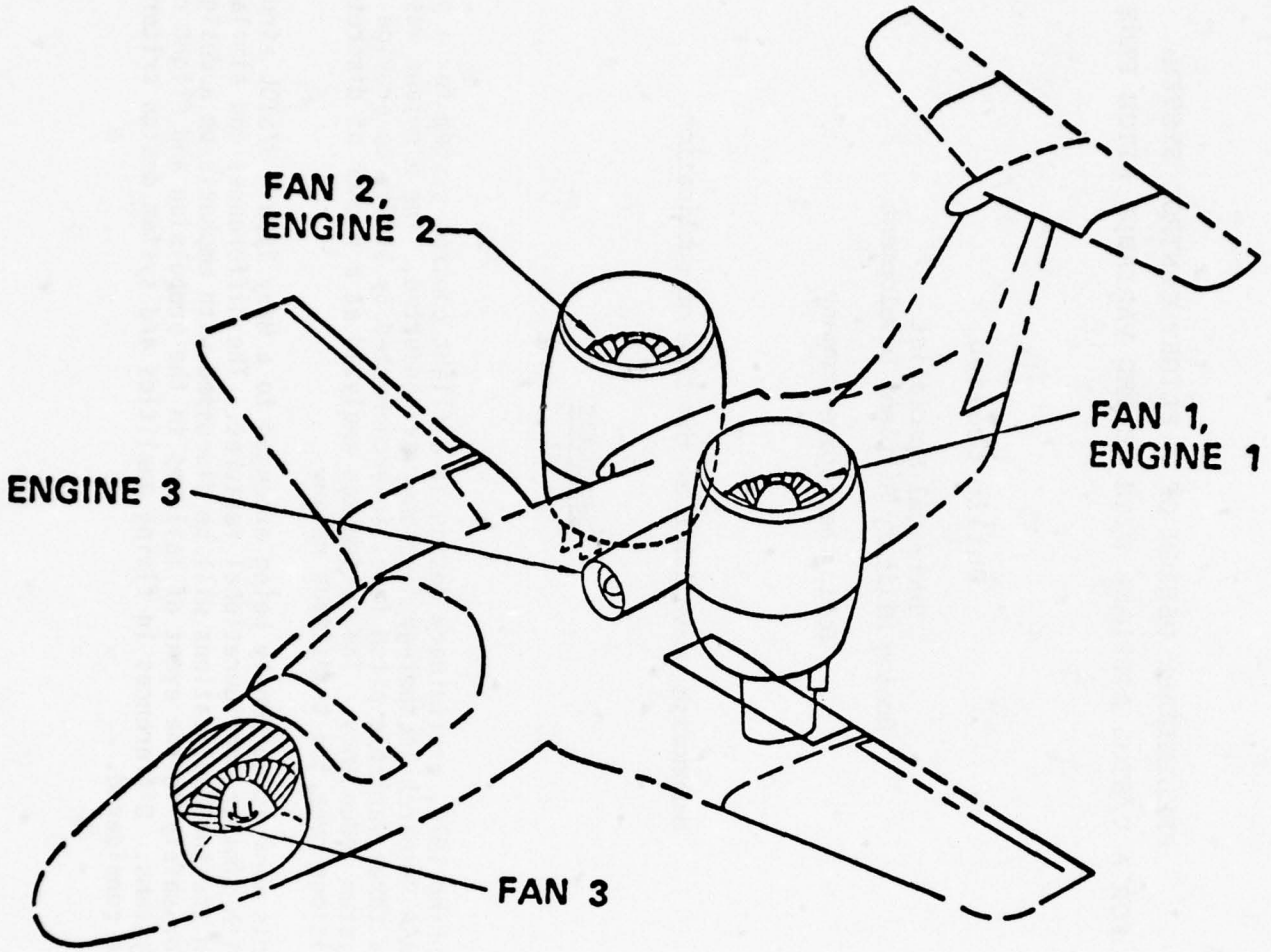
ABSTRACT

During 1976, preliminary design of a flight control system for a proposed NASA Research Technology Airplane was conducted. The airplane was powered by three variable pitch fans, interconnected by shafts to provide lifting system redundancy. The system was analyzed at a number of discrete conditions over the transition range.

This work is currently being extended to a Navy Type A V/STOL airplane with similar configurational features. The differences and similarities in the two applications will be discussed with emphasis on a design approach for safety in the event of failures in the propulsion and flight control systems. Differences in flying qualities and system design criteria will be considered.

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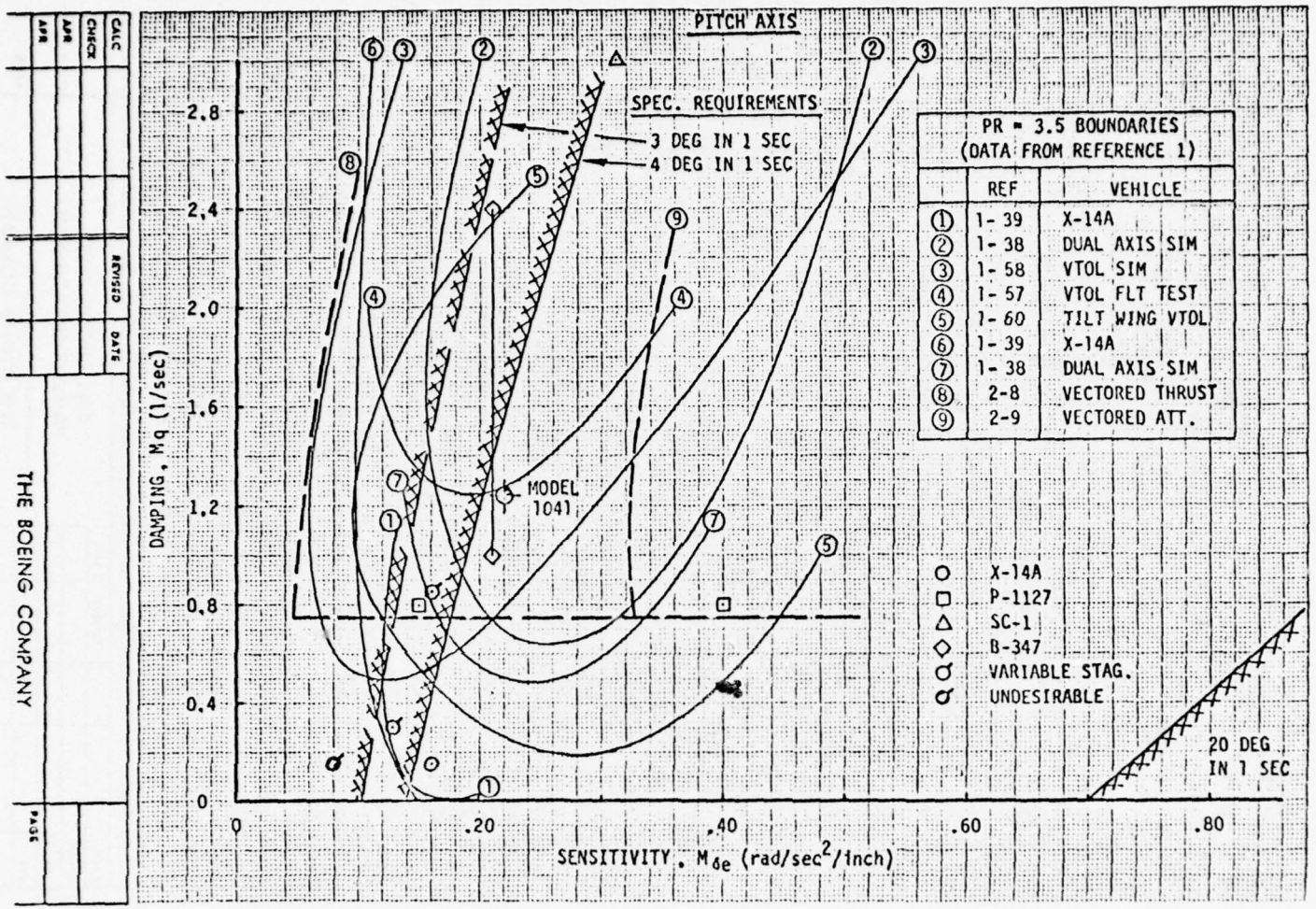
AIRPLANE ISOMETRIC



Navy Multimission Studies

Control Laws

Pilot control	Speed range		
	Hover and low speed	Higher transition speeds	Cruise
Longitudinal stick	Pitch attitude with drift velocity	Pitch rate with attitude hold	Pitch rate with attitude hold
Lateral stick	Side velocity	$\phi < 4^{o}$ bank angle $\phi > 4^{o}$ roll rate with bank angle hold turn coordination	ROLL RATE With bank angle hold turn coordination
Rudder pedals	Yaw rate with heading hold	Yaw rate	Yaw rate
Throttle lever	Rate of climb w[illegible]itude h[illegible]	Rate of climb	Fan thrust (pilot option)
Speed switch	Ground speed	Ground speed/airspeed (pilot option)	Ground speed/airspeed (pilot option)


PITCH AXIS
SPEC. REQUIREMENTS
3 DEG IN 1 SEC
4 DEG IN 1 SEC
PR = 3.5 BOUNDARIES
(DATA FROM REFERENCE 1)
REF
VEHICLE
1 1-39 X-14A
2 1-38 DUAL AXIS SIM
3 1-58 VTOL SIM
4 1-57 VTOL FLT TEST
5 1-60 TILT WING VTOL
6 1-39 X-14A
7 1-38 DUAL AXIS SIM
8 2-8 VECTORED THRUST
9 2-9 VECTORED ATT.
MODEL 1041
X-14A
P-1127
SC-1
B-347
VARIABLE STAG.
UNDESIRABLE
20 DEG IN 1 SEC
DAMPING, Mq (1/sec)
SENSITIVITY, M$_{\delta e}$ (rad/sec^2/inch)
0
.20
.40
.60
.80
0.4
0.8
1.2
1.6
2.0
2.4
2.8
CALC
CHECK
REVISED
DATE
PAGE
THE BOEING COMPANY

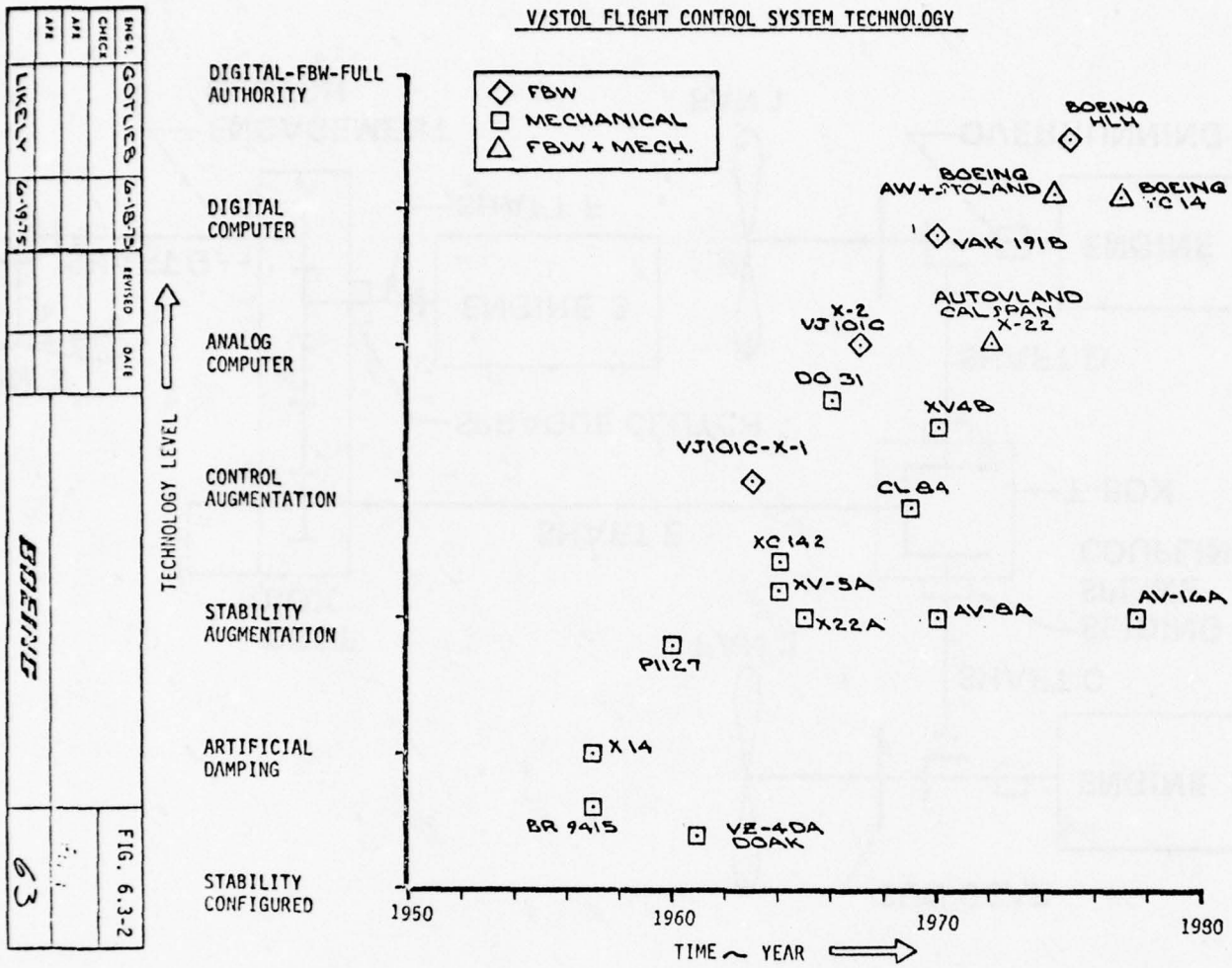
SYMBOL
TEST
REFERENCE
TEST YEAR
CRITERION
BOEING US/FRG SIMULATIONS
BOEING D6-15709
1967
PR 3.5
BOEING SEA CONTROL FIGHTER SIMULATIONS
BOEING D180-18008
1973
$\ddot{\Phi}$ .98
UNITED AIRCRAFT SIMULATIONS
APPDL TR-73-34
1973
$\ddot{\Phi}$ .95
ATTITUDE CONTROL
MIL 83300 REQUIREMENT
$\ddot{\Phi}$ (RAD/SEC^2)
0.6
0.5
0.4
0.3
0.2
0.1
0
$2.0|L_v|\sigma_v$
0.3
0
.1
.2
.3
RMS TURBULENCE, $\ddot{\Phi}_T = |L_v|\sigma_v$ (RAD/SEC^2)
CALC
CHECK
APR
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ROLL CONTROL POWER
MANEUVER AND STABILIZE
THE BOEING COMPANY
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Hover Control Design Criteria Comparison

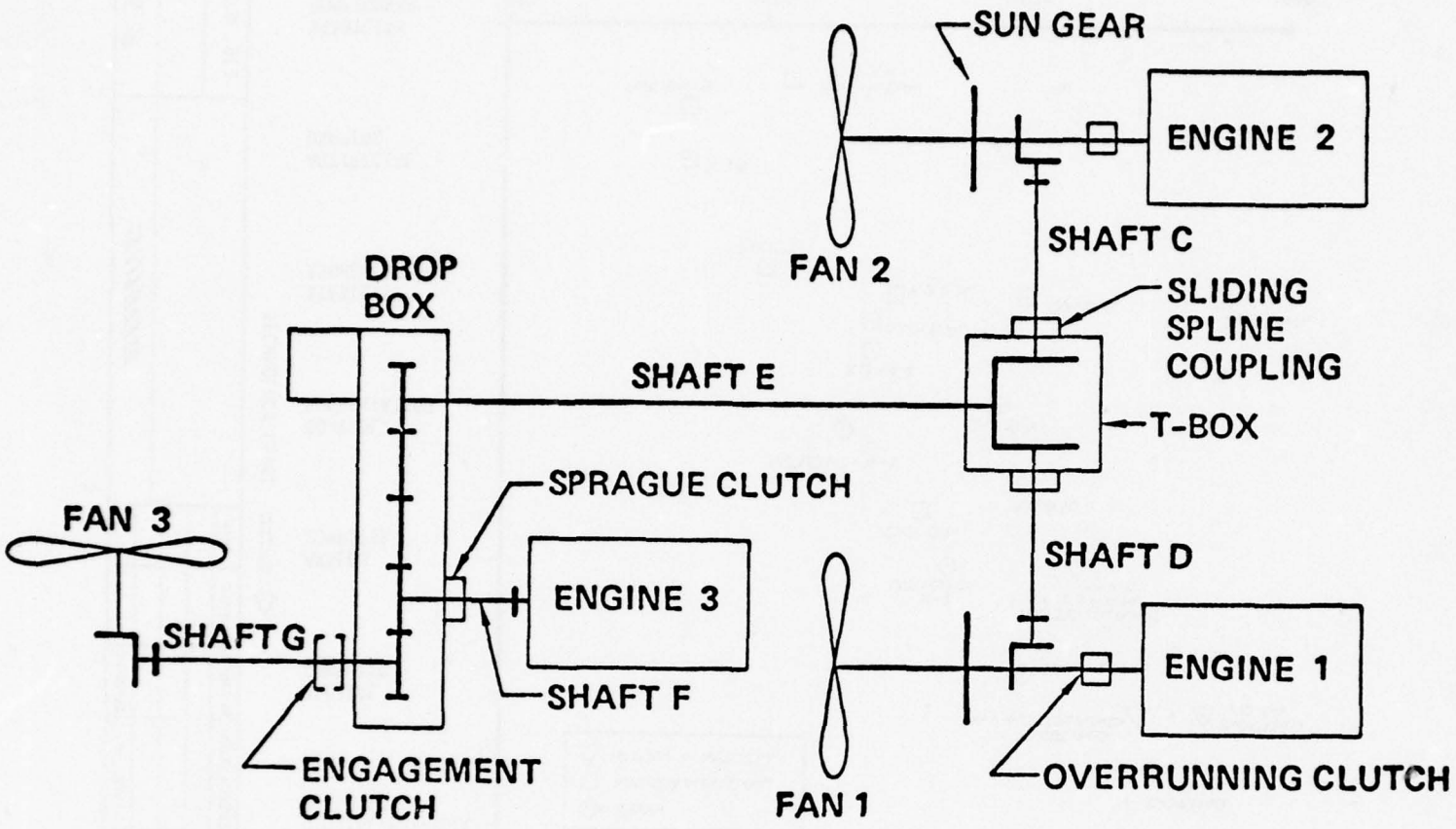
MIL-F-83300 1971	NASA RTA 1974	Boeing (Navy tactical) 1974
• Total installed power $\ddot{\phi} = 1.6\ r/s^2$ $\ddot{\theta} = 1.0\ r/s^2$ $\ddot{\psi} = 0.6\ r/s^2$ • Hover in 35 kn wind one inch control remaining	• For maneuver only $\ddot{\phi} = .90$ $\ddot{\theta} = .50$ $\ddot{\psi} = .30$ • Hover in 25 kn wind 50% maneuver remaining	• For maneuver and stabilization $\ddot{\phi} = .3$ + gust sens factor $\ddot{\theta} = .3$ + gust sens factor $\ddot{\psi} = .16$ + gust sens factor • Account for all other known trim and upset conditions separately

FCS Technology for 1990 IOC

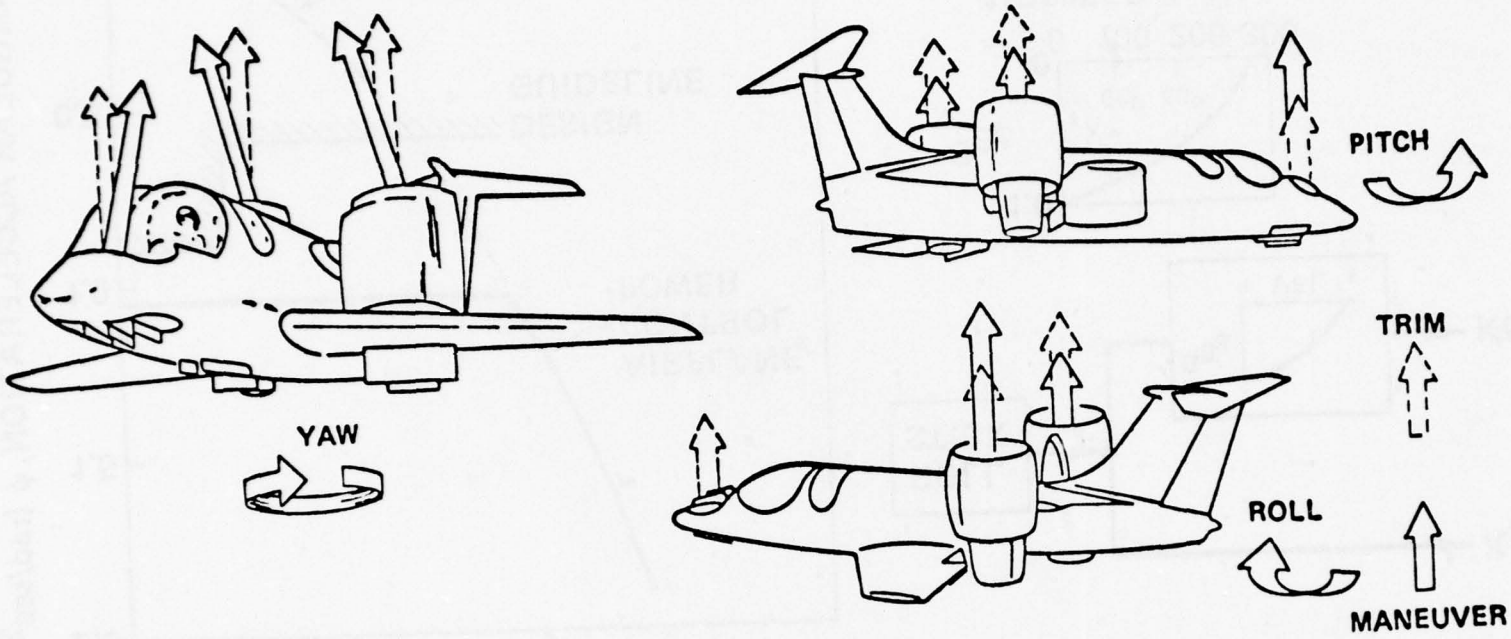
- Tailored flight control laws
- Redundant federated digital logic — Bite
- Integrated propulsion and flight control systems
- Fly by wire
- Modular components — four configurations
- Side arm controllers
- Augmented visibility
- Strapdown skewed gyros
- Dual triplex redundancy — 2 fail operational


V/STOL FLIGHT CONTROL SYSTEM TECHNOLOGY
FBW
MECHANICAL
FBW + MECH.
DIGITAL-FBW-FULL AUTHORITY
DIGITAL COMPUTER
ANALOG COMPUTER
CONTROL AUGMENTATION
STABILITY AUGMENTATION
ARTIFICIAL DAMPING
STABILITY CONFIGURED
TECHNOLOGY LEVEL
BOEING HLH
BOEING AW+STOLAND
BOEING YC 14
VAK 191B
AUTOVLAND CALSPAN X-22
X-2 VJ101C
DO 31
XV4B
VJ101C-X-1
CL84
XC142
XV-5A
X22A
AV-8A
AV-16A
P1127
X14
BR 9415
VE-40A DOAK
1950
1960
1970
1980
TIME ~ YEAR
ENGR.
CHECK
APP.
APP.
GOTLIEB
6-18-75
REVISED
DATE
LIKELY
6-19-75
BOEING
63
FIG. 6.3-2

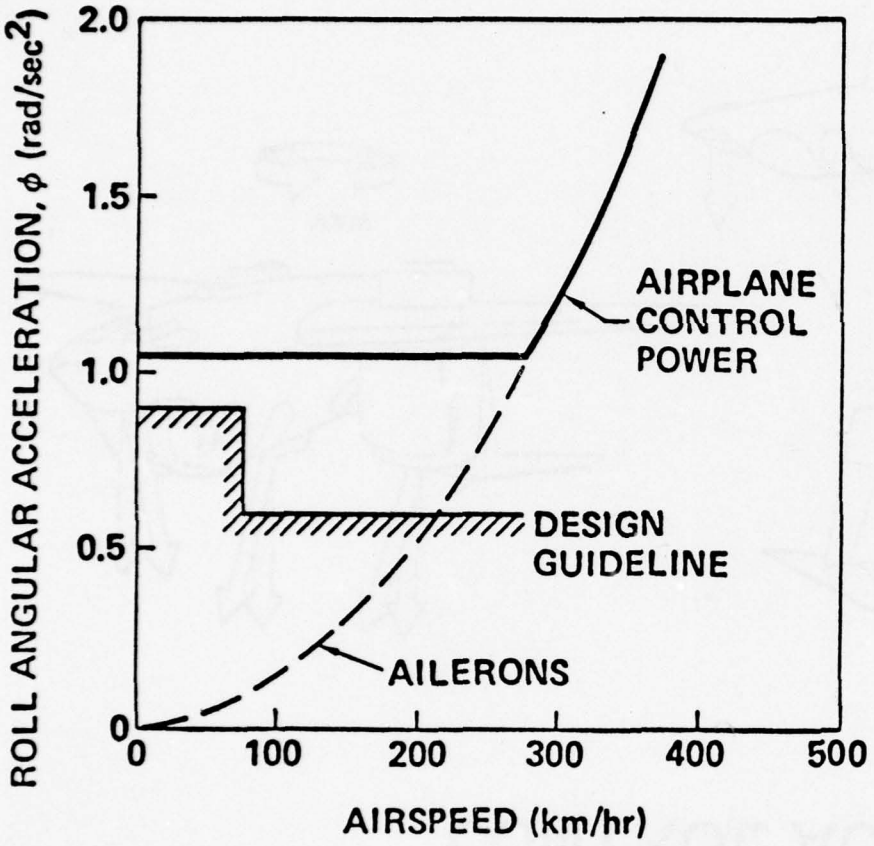
PROPULSION SYSTEM SCHEMATIC

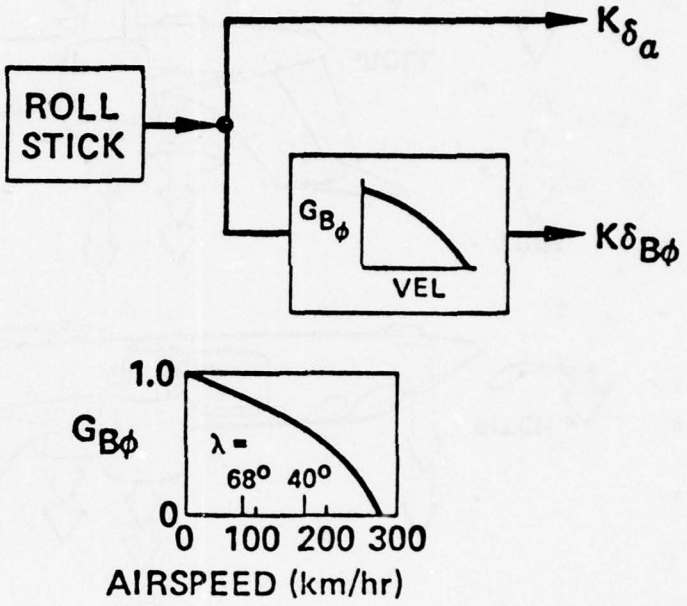


CONTROL ACTION

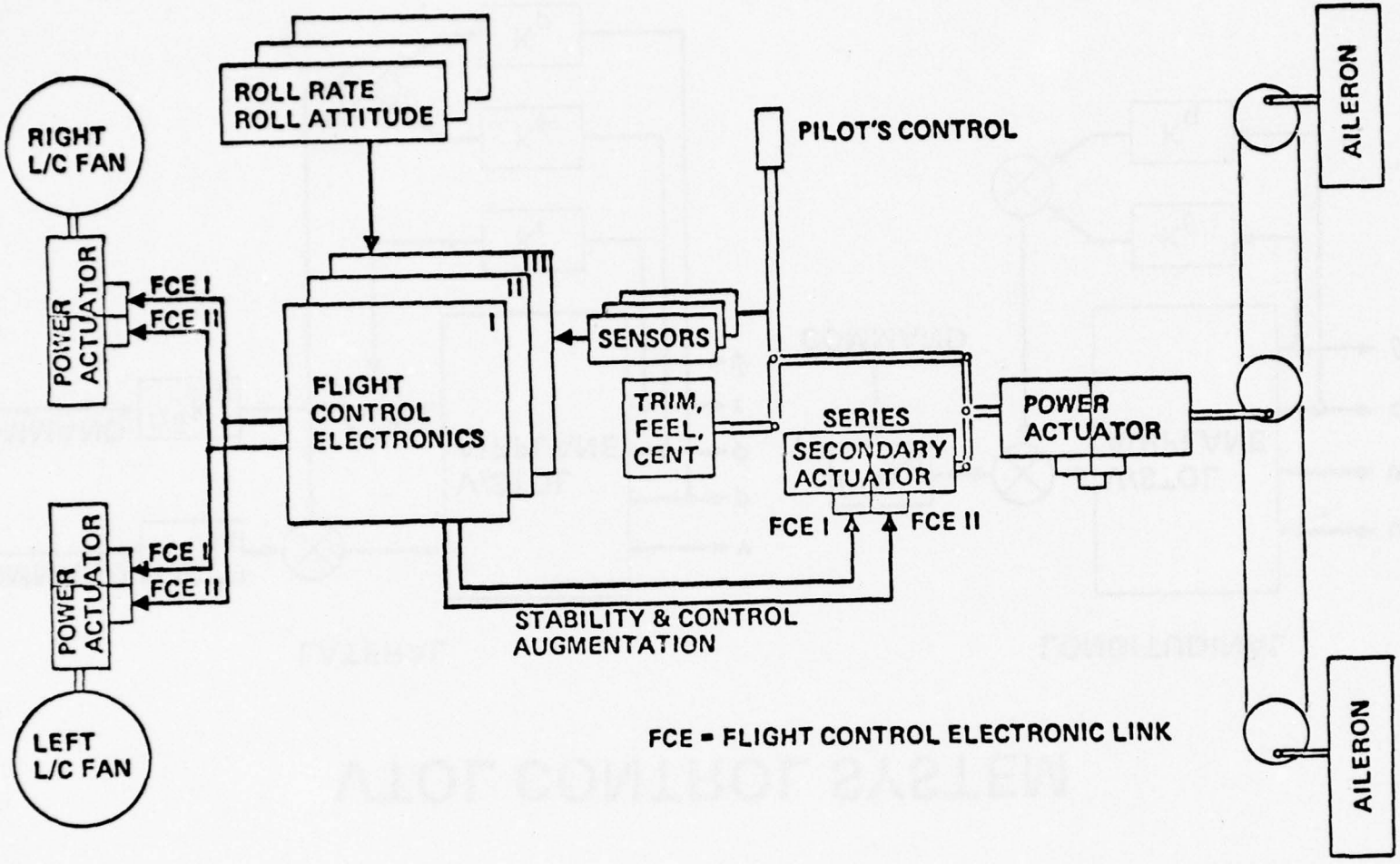


INTEGRATED ROLL CONTROL POWER

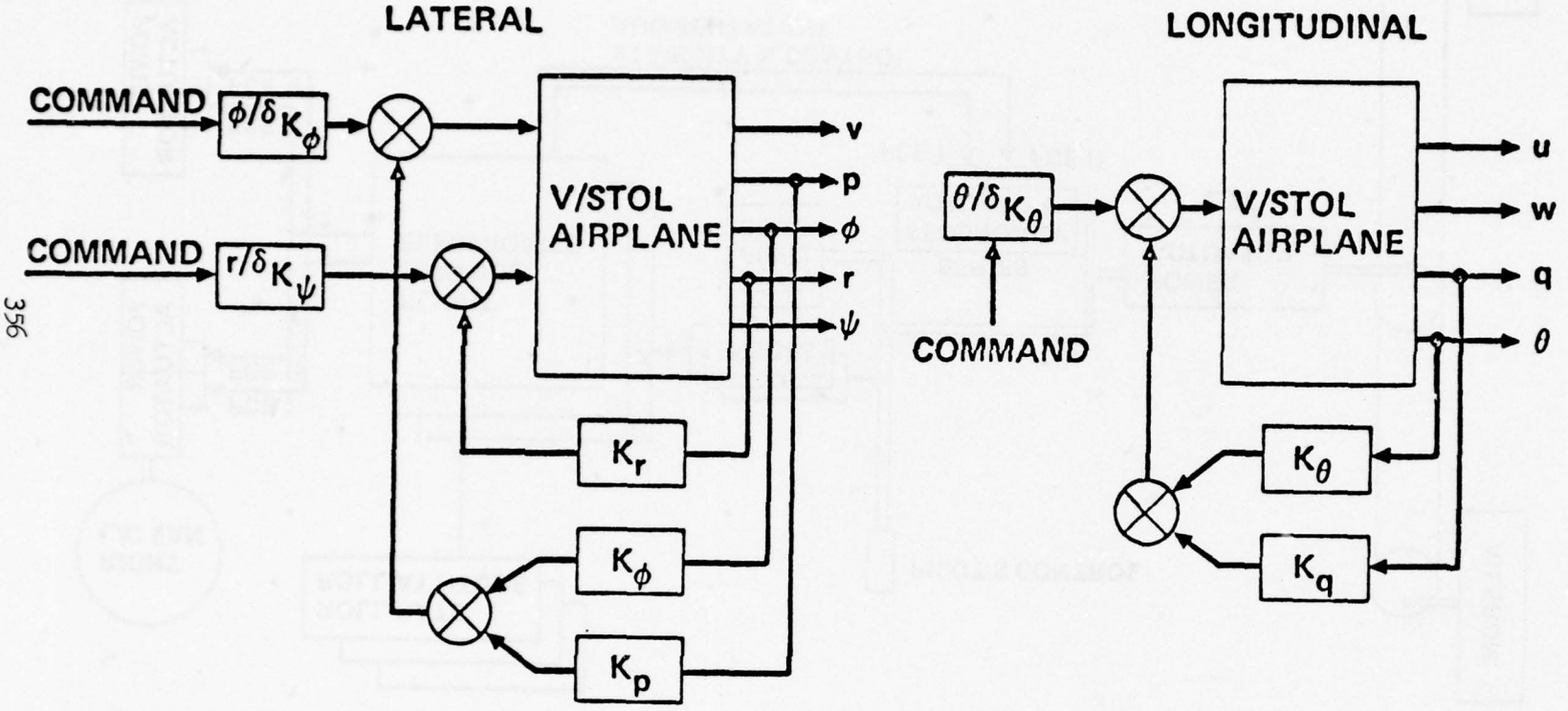




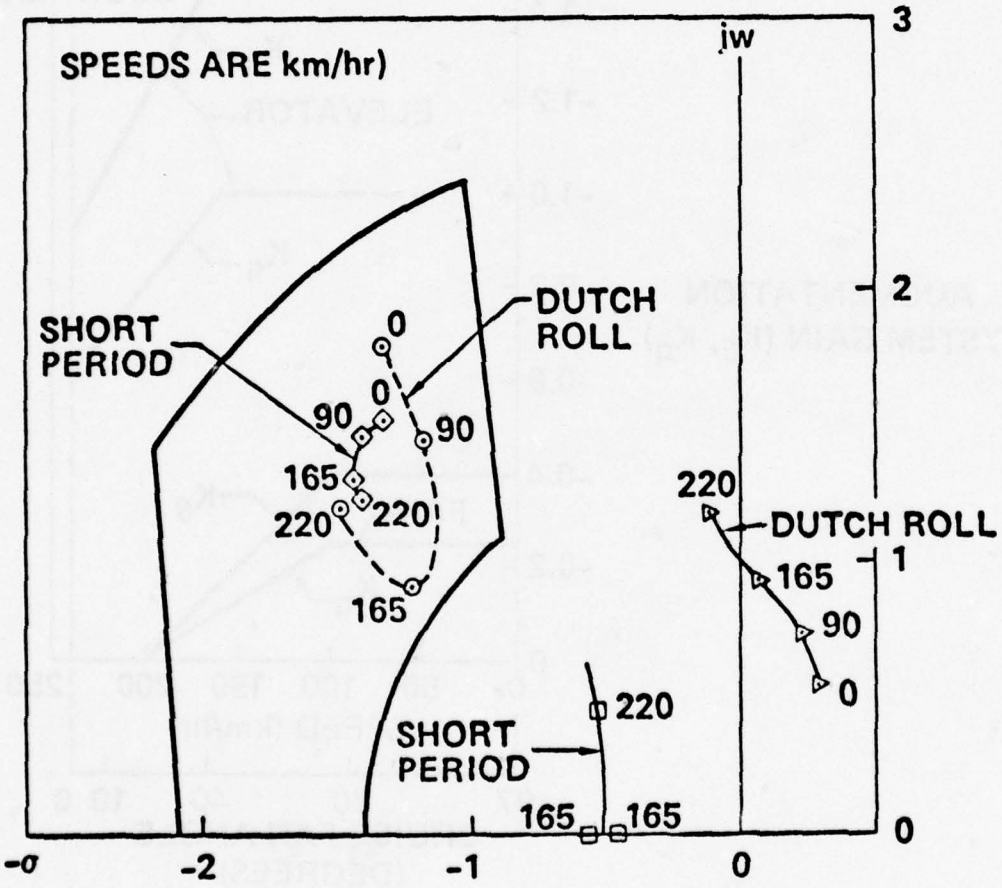
ROLL CONTROL SCHEMATIC



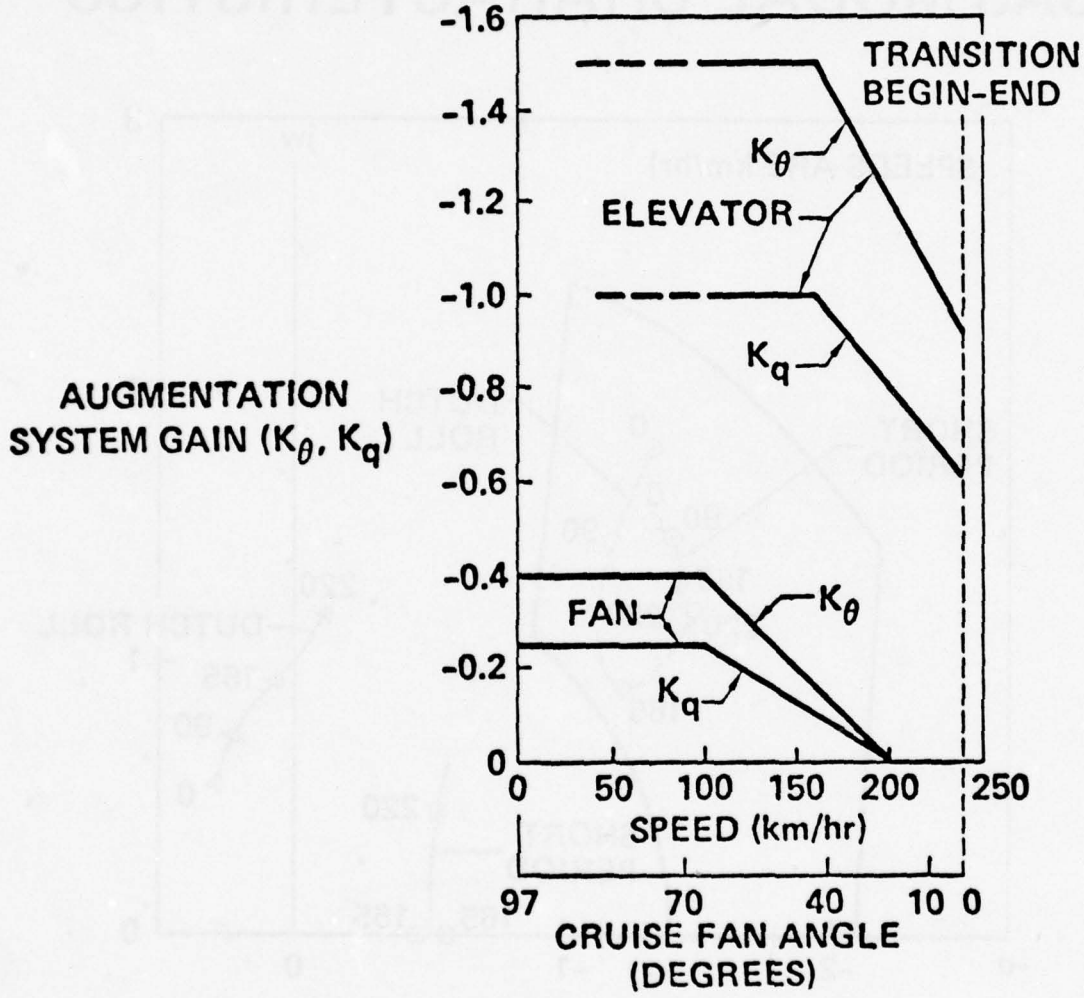
VTOL CONTROL SYSTEM



SAS MODAL CHARACTERISTICS



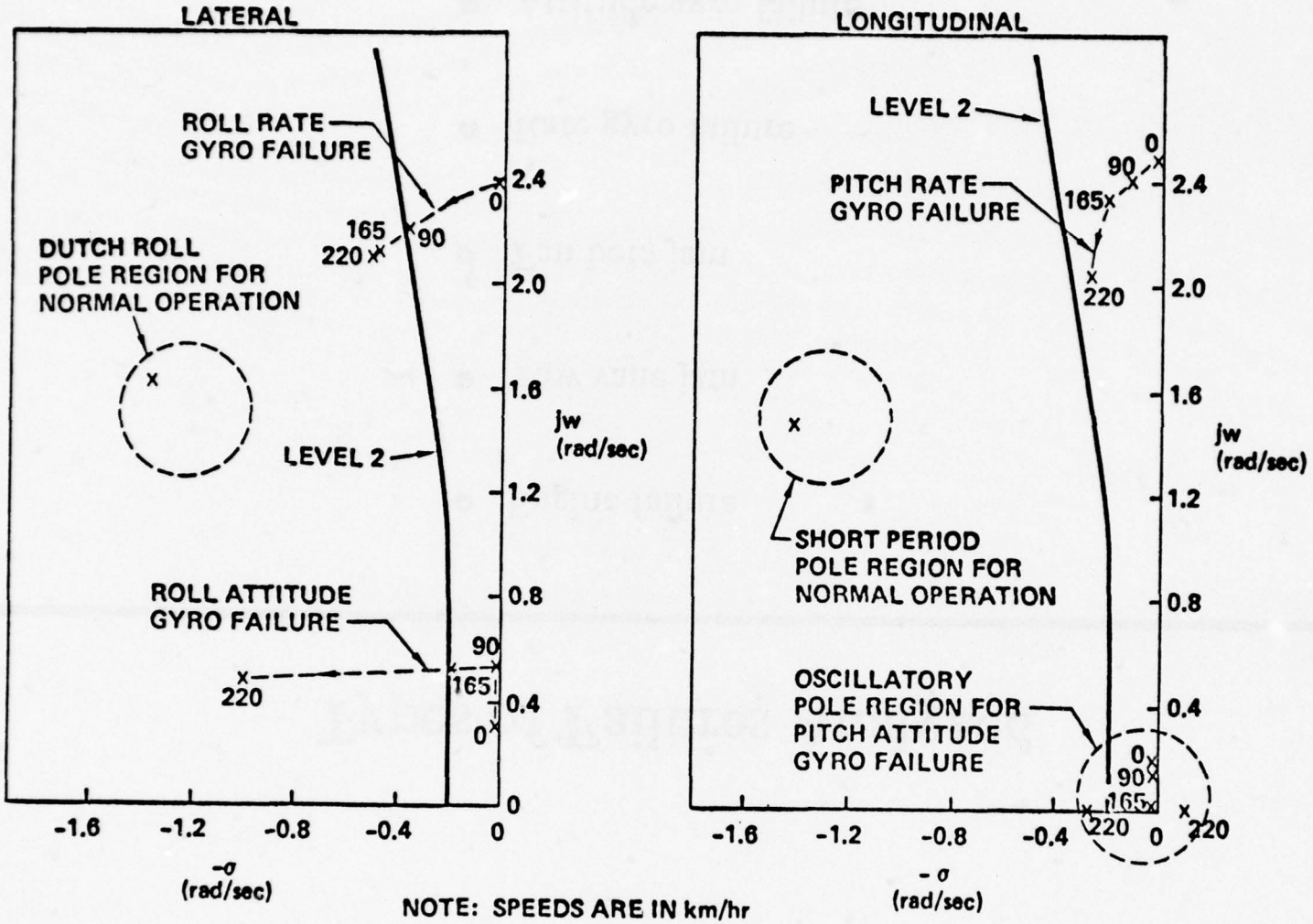
GAIN SCHEDULE: LONGITUDINAL



Types of Failures Analyzed

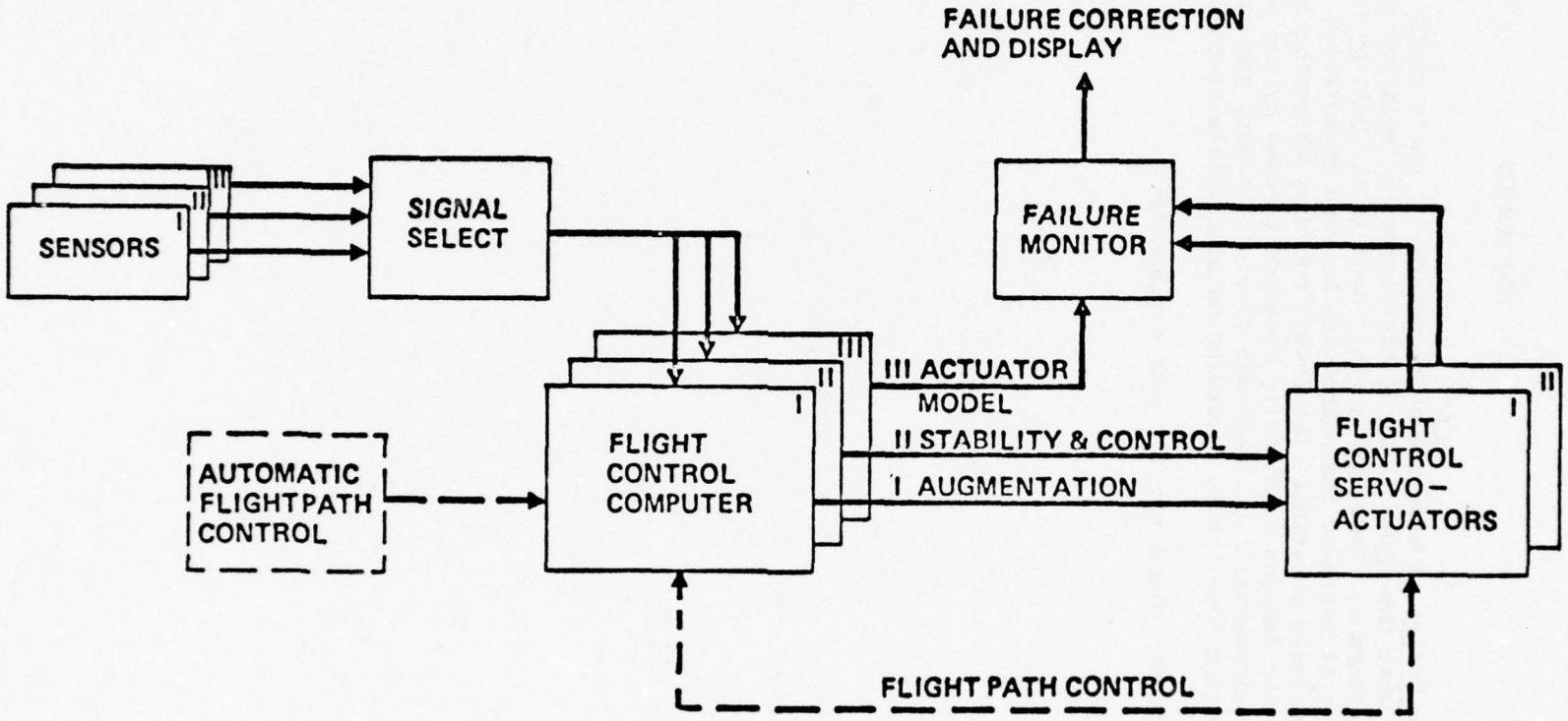
- Engine failure
- Yaw vane jam
- Fan beta jam
- Rate gyro failure
- Attitude gyro failure

SENSOR FAILURE



NOTE: SPEEDS ARE IN km/hr

FLIGHT CONTROL SYSTEM REDUNDANCY LEVELS



DISCUSSION

Sam Craig: I have one quick remark. I can't resist answering your question on what the upper limit of that curve is (relative to a slide that was displayed). There was a study done in the U.K. by Barnes and McPherson that illustrated the compromise between maneuvering requirements and precision hovering. The lowest boundary where the data generally lies is the damping sensitivity boundary imposed by the pilot's response requirements; i.e., maintain precision hover, yet sustain maneuverability. (Editor note: tape recording unintelligible at this point.)

Gotlieb: Thank you for your explanation.

ELECTRONICS PLUS FLUIDICS FOR V/STOL FLIGHT CONTROL

RUSSELL C. HENDRICK, STAFF ENGINEER
AVIONICS DIVISION - HONEYWELL, INC.

INTRODUCTION

Demanding stabilization requirements combined with the complexities of varying geometry and coupled control axes make the fly-by-wire flight control system a leading candidate for the V/STOL airplane. Associated use of digital computation facilitates control law sophistication while alleviating maintenance problems through superior self-test provisions. A unique potential partner to the redundant digital flight control system is a fluidic system, which uses hydraulic pressure as its signal transmission means to provide pilot and feedback sensor control of airframe forcing functions. The resulting hybrid system offers dissimilar redundancy benefits for added protection against design and environmental uncertainties. The conventional mechanical primary flight control system (PFCS) with electronic augmentation also has dissimilar redundancy benefits, but the lack of feedback augmentation in the mechanical system plus the costs associated with V/STOL configuration complexities make its use undesirable. A new candidate for the traditional role of the mechanical PFCS is the fluidic system, which has the combination of modest performance and high reliability that is appropriate for a backup flight control function.

Both fly-by-wire and fluidic systems have been under active development for over a decade, as indicated by Figure 1, and both types of systems have been designed for a production aircraft (e.g., the F-16 and the UTTAS helicopter). However, only the Fly-by-Tube Program, a design and laboratory testing series (1973-76) sponsored by the Naval Air Systems Command and recently by the Army Air Mobility Research and Development Laboratory, has focused on the use of fluidics as a primary flight control means and the techniques for integrating it with other system types. This paper presents technical issues significant to the design of a hybrid electronic/fluidic flight control system with particular attention to the V/STOL application. A potential fluidics system is introduced, and anticipated performance, weight, and reliability is discussed. Its integration with the redundant electronic channels is explored, with the safety and mission reliability of alternate configurations estimated.

FLUIDIC SYSTEM DESIGN

A block diagram of a basic fluidic control channel applicable to one V/STOL control axis is shown in Figure 2. An input position signal (e.g., from a control stick or rudder pedals) is combined with angular rate feedback to produce actuator deflections via a scheduling element. The latter provides gain variations to accommodate the airframe geometry changes typical to the transition between forward and hovering flight, allocating the input signals to the appropriate actuators. These geometry changes may be wing angle, nacelle angle, nozzle position, or other elements unique to the particular airframe. Also associated with the signal distribution process is the application of the combined input signals to other schedulers and the addition of other actuator inputs from other control axes. Generally, this arrangement for resolving control axis inputs to multiple actuators is typical of the lateral-directional axes. The indicated use of angular rate as the sole feedback signal reflects the minimum expected augmentation for the pitch, roll, and yaw axes. Other fluidic sensors are available, such as a linear accelerometer. The rate sensor, in combination with lag-lead shaping, can provide a short-term attitude stabilization that may be adequate for the hover mode and still acceptable for forward flight. The shaping on the input position signal may not be required, or, at most, a small (e.g., 0.1 second) low-pass filter may be necessary. The indicated synchronization around the actuator is provided to make the fluidic channel track the electronics when the latter is controlling to avoid switching transients. More will be said about this later.

The basic control channel of Figure 2, combined with other control axes, may comprise an installation similar to that illustrated for the helicopter shown in Figure 3. Each channel requires a pair of tubes to transmit the pressures whose difference constitutes the fluidic signal.

FLUIDIC COMPONENTS

The following paragraphs briefly describe the major elements of the fluidic system.

Mechanical Input Transducer

This device (Figure 4) produces a differential pressure proportional to the deflection of a mechanical input, potentially a control stick, rudder pedals, or some variable geometry element of the airframe. The mechanical input applies a force to a nozzle-flapper valve with a

differential pressure feedback. Other types of inputs may also be applied in parallel with the mechanical, such as an electrical torque motor for preflight test purposes. A large output range (e.g., ±400 psid) is generally selected to reduce amplification requirements.

Shaping and Amplification

Examples of fluidic shaping and amplification are shown in Figure 5. Dynamic shaping is produced by combining flow resistance (orifices) and capacitance (bellows) in such a way to regulate the rate of change of differential pressure. For the lag shaping illustrated, a change in output differential pressure requires flow into or out of the bellows, hence a lag. The bellows and orifice arrangement is varied to provide other types of compensation such as a high-pass. The amplifier produces an increase in the output signal proportional to the input. There are many types of amplifiers, but the most widely used is the jet deflection amplifier shown in Figure 5. The supply pressure produces a jet, which, in the absence of an input pressure differential, is divided equally between the two output legs. If a differential control signal is applied to the control ports, the jet is deflected proportionally, resulting in output pressure differential. The expanded area between the control ports and the output legs provides a low impedance flow path between the two sides of the power jet, which is necessary to achieve a proportional rather than a bistable action.

Vortex Rate Sensor

The rate sensor produces an output pressure differential proportional to the angular rate of the case about its input axis. Many types have been developed, but the vortex sensor, shown schematically in Figure 6, is by far the most highly developed and applied. The flowing fluid (e.g., hydraulic oil) enters a plenum chamber, from which it is equally distributed to a vortex chamber, thence out the sink to a region of lower pressure. With no turning rate of the case, the streamlines are radial lines to the sink, and no pressure differential occurs across the output pickoff element. With a turning rate of the case, however, the streamlines assume a spiral character, causing a pressure output proportional to the degree of vorticity, hence the turning rate. The device is preflight tested by deflecting a vane in the vortex chamber which causes an output differential.

Summing and Scheduling

Fluidic summing is performed by a combination of orifices, as shown in Figure 7 for a case of two inputs. If a gain variation is desired for scheduling purposes, the orifices may be mechanically varied. Each input produces a portion of the return flow, hence a portion of the output pressure differential. Operating pressure levels are selected to produce a summation that is essentially linear.

Fluidic Actuation

Figure 8 illustrates the portion of an integrated actuator operated by the fluidic channel. The actuator piston shown is one-half of a dual-tandem primary actuator, driven by either fluidic or electronic channels, depending on the position of the transfer valve (shown in the fly-by-wire position). Input control pressures from the fluidic channel applied to force capsules produce a torque on a nozzle flapper assembly. The flapper valve produces a differential pressure across a spool valve, which moves an amount determined by a force feedback spring that recenters the flapper. The spool valve controls flow to the actuator piston if the transfer valve is in the "fluidic" position. Motion of the piston is mechanically fed back to recenter both the flapper valve and the spool valve. The final result is a piston position proportional to input control pressure.

SYSTEM INTEGRATION

The fluidic and electronic channels are ideally combined within an integrated actuator assembly, as shown in Figure 9. The fluidic portion, previously shown in Figure 8, includes the fluidic controlled valve spool, the transfer valve, and the left side of the tandem actuator. The electronic portions include valve spool control means for both sides of the tandem actuator. These are driven and monitored by redundant electronic channels which generally apply torque motor currents to dual electrohydraulic valves for each valve spool, with the ram position fed back electrically to servo loop electronics.

Requirements for combining the electronic and fluidic channels include:

- Acceptable switching transients
- Capability for going either way
- Provision of nominal control qualities immediately after switching (e.g., no transient gain reduction)

- Automatic switching from electronic to fluidic after total (not partial) electronics failure
- Pilot selection capability

The first three requirements are conceptually illustrated by Figure 10. Note that each channel is synchronized to the other when the other is controlling. When the switch occurs, no immediate change in the net control position occurs. Immediately after the switch, however, the controlling channel has full nominal gain, an important feature if stabilization qualities are to be retained during the transition. Any mistrack between the actual and the synchronized command levels slowly bleeds off after the switch, similar in effect to changing aircraft trim.

PERFORMANCE

Fluidic Channel Qualities

The properties of gain stability, null stability, bandwidth, and resolution of the basic fluidic channel are summarized in Figure 11 along with their principal influences. The state-of-the-art performance levels achievable for these characteristics are considered satisfactory for backup control functions. The principal influence is commonly fluid viscosity, and this temperature-related parameter has been the subject of many of the fluidic developments over the past decade. Viscosity-sensing elements are now used to stabilize system performance by varying flow rates appropriately. Transmission lines that use closed volumes of low-viscosity silicone fluid have been designed to attain high bandwidths at low temperatures.

Stability Augmentation

The optimum augmentation for a V/STOL aircraft in terms of control quality varies from some form of velocity stabilization at hover to a conventional acceleration/rate response during conventional forward flight, as illustrated by Figure 12. An extensive complement of motion sensors plus the power of digital computation in executing control laws appropriate to the flight condition as well as the mission task is a demonstrated technology. For the fluidic system, however, altered compromises between complexity and performance are appropriate. A fixed (hence simple) system configuration capable of providing satisfactory (albeit different) performance at specific flight phases should be considered. An example of such a compromise is shown in Figure 13 for a hypothetical pitch axis which varies from essentially a pure inertia at hover to a conventional short-period response with positive

damping at high-speed cruise. Also associated with the change in dynamics is a 10 to 1 change in surface effectiveness. The fluidic system is configured with fixed parameters to produce short-term attitude stabilization while observing adequate stability margins. The resulting responses indicate good controllability over the flight range, the only question being the adequacy for landing under difficult conditions. Further work is necessary to answer this question.

WEIGHT ESTIMATES

Weight estimates for a four-axis fluidic system and a comparable electronic channel are presented in Figure 14. The fluidic system weight is dominated by the required hydraulic piping, hence the relevance to vehicle size is evident. The indicated line lengths were based on the UTTAS helicopter (21,000 pound gross). The electronic channel weight is based on state-of-art digital flight control hardware with analog input/output, sensors, and servo interfaces.

It is evident that the fluidic system weight is substantial, and that its acceptability will depend in part on an associated savings in electronic equipment. If an electronic channel can be traded for a fluidic channel, the net weight penalty would be reduced to 25 pounds.

FLUIDIC FAILURE RATE ESTIMATE

Figure 15 summarizes a failure-rate breakdown for a four-axis fluidic system. The component failure rates were developed from a piece-part analysis of each assembly. The dominance of the secondary servo (valve spool control loop) in the overall rate is evident.

REDUNDANCY CONFIGURATIONS

Potential redundancy configurations for the hybrid electronic-fluidic system are identified in Figure 16. One fluidic channel, dual hydraulic supplies, and between two and four electronic channels comprise the selected components, from which three alternate systems are defined, each with the fluidic channel, the dual hydraulics, and two, three or four electronic channels. Dual hydraulics are assumed because of demonstrated need and adequacy for the subject class of aircraft. A single fluidics channel is considered adequate for a backup role, recognizing the need for a thorough preflight test. The numbers of electronic channels reflect results of past fly-by-wire studies (either three or four is considered adequate even without a backup) plus the assumption that the fluidic channel may allow the deletion of one electronic channel. Also indicated on Figure 16 are nominal failure rates (per

hour) for the three major elements. The fluidics rate is taken from Figure 15, the electronics rate is based on the breakdown shown in Figure 16, and the hydraulic rate is based on Navy operational data. Certain other failure sources (such as mechanical jams in dual-tandem actuators) that are common to all configurations are not included. The identified failure sources will be used to make rough reliability comparisons between alternate systems. A better description of each candidate plus the associated reliability estimates follow.

In computing the mission and safety reliabilities, each channel is considered as a series string of components, which is a pessimistic assumption in that benefits due to sensor crossfeeding and axis separation are not considered. Because the hydraulic supplies dominate the final results, however, the simple reliability models used do not significantly affect the general conclusions. All elements are assumed operable at takeoff, and comparison monitoring is assumed to be 100-percent effective. Reliabilities apply to a one-hour flight.

Dual Electronics

The electronic channels here use a combination of comparison monitoring and self test to detect and isolate failures. Comparison monitoring detects first failures, which are then isolated by the computer testing itself as well as associated sensors and servo interfaces. The assumed coverage (probability of detecting a fault by self test) is denoted $1-D_T$, where D_T is the test deficiency (probability of not detecting a fault). A switch to the fluidic channel occurs for two situations:

- After the first electronic failure, if the self test does not isolate the faulty channel after the comparison monitor detects the fault. This has a probability of $2Q_E D_T$.

- After the second electronic failure, both having been properly isolated by self test, a probability of $Q_E^2 (1-D_T)^2$

Both of these situations result in mission abort, as it may be that the fluidic channel is generally unsatisfactory to accomplish the mission, and a subsequent failure may be catastrophic (e.g., loss of number one hydraulics). Because of the latter reason, loss of either hydraulic systems also results in an abort, a probability of $2Q_H$.

Total system failure (a catastrophy) occurs for any of the following three situations:

- Two electronic failures, the first being detected by self test and the second not, a probability of $Q_E^2 (1-D_T)D_T$

- One electronic failure, followed by a self-test failure, a switch to fluidic, and a fluidic failure, a probability of $2Q_E D_T(Q_F + Q_H)$.

  (Note that a fluidic failure occurs for either a fluidic component fault or loss of number one hydraulics.)

- Failure of both hydraulic systems, a probability of Q_H^2.

The total series failure rate of the dual system considered here is $2Q_E + Q_F + 2Q_H$, giving an MTBF of 300 hours.

Triple Electronics

The electronics here also use a combination of comparison monitoring plus self test, but the self test does not play an essential role in failure detection until after the second electronic failure. The first electronic failure is detected and isolated by comparison monitoring and voting. If a second electronic failure occurs, detection is performed by comparison, but isolation by self test of the electronics as described for the dual system is required. A switch to the fluidic channel is executed (hence an abort) for the following two cases:

- Two electronic failures plus a self-test failure, a probability of $3Q_E^2 D_T$.

- Three electronic failures, the second and third having been successfully detected or isolated by self test, a probability of $Q_E^3(1-D_T)^2$

A third abort source is failure of either hydraulic supply, which has a probability of $2Q_H$.

Total system, or catastrophic, failure occurs after any of the following four cases:

- Three electronic failures with proper isolation plus a fluidic failure, a probability of $Q_E^3(1-D_T)^2(Q_F + Q_H)$.

- Two electronic failures, a self-test failure, and a fluidics failure, a probability of $3Q_E^2 D_T(Q_F + Q_H)$.

- Three electronic failures, the second having been properly self tested but the third improperly self tested, a probability of $Q_E^3(1-D_T)D_T$.

- Two hydraulic failures, a probability of Q_H^2.

The total series failure rate of the triple system considered here is $3Q_E + Q_F + 2Q_H$) giving an MTBF of 231 hours.

Quad Electronics

The quad electronics can use conventional comparison monitoring and voting to achieve dual-fail-operative, fail-safe qualities. A switch to fluidic will occur after three electronic failures, a probability of $4Q_E^3$. This, plus the probability ($2Q_N$) of a single hydraulic failure, determines the abort rate. A total system failure occurs after either of two events:

- Three electronic plus one fluidic failure, a probability of $4Q_E^3(Q_F + Q_H)$.

- Two hydraulic failures, which has a probability of Q_H^2.

The total series failure rate of the quad system is $4Q_E + Q_F + 2Q_H$, giving an MTBF of 188 hours.

Comparative Reliabilities

Using the preceding models and numerical data, the comparative reliabilities, based on random component failures, are summarized in Figure 17. The mission and safety figures for the dual and triple systems are based on a 95-percent self-test coverage ($D_T = 0.05$), an average value which is believed to be within the state of the art for the equipment delegated to the electronics channel. Two notable results are indicated in Figure 17:

- The differences between systems in terms of safety and mission reliability are small, simply because the hydraulic failure rates dominate both qualities.

- The values of mission and safety reliability for all candidates appear satisfactory in terms of potential specifications for the associated equipment.

CONCLUSIONS

Safety

Safety is the primary reason for considering a hybrid electronic/fluidic system. The dissimilar redundancy offers added protection against unknown or unpredicted events and environments. For purely random component failure, both the fly-by-wire and the hybrid systems have essentially equal predicted safety, paced by hydraulic and mechanical failures.

Performance

This is a major technical question for the fluidic system, whether the performance it affords is adequate for a backup role in a sufficiently large percentage of the missions.

Mission Reliability

Abort rate is essentially the same for both the fly-by-wire and hybrid systems, paced by the hydraulics.

Weight

If an electronic channel can be deleted by having the fluidic channel, the hybrid system will have a weight penalty on the order of 25 pounds per aircraft. If not, the weight penalty is about 65 pounds.

Acquisition Cost

The initial costs of a fluidic channel and an electronic channel appear roughly equal. The specific applications must be assessed for this quality, but it is not expected to be a major factor in system selection.

Maintenance

The basic MTBF appears slightly lower for a fly-by-wire system than a hybrid system (assuming an electronic channel is replaced by a fluidic channel). However, the maintenance effort per failure is probably higher for the fluidic. The net difference is not expected to be large.

Survivability

The ability to withstand total electrical failure contributes to the survivability of the hybrid system.

FLY-BY-WIRE:

- SURVIVABLE FLIGHT CONTROL (F4 TEST)
- NASA F-8
- HEAVY-LIFT HELICOPTER
- SPACE SHUTTLE
- F-16
- F-18

FLUIDICS:

- CH-46 SAS TEST
- UH-1 SAS, SCAS, AUTOPILOT TESTS
- JET RANGER/OH-58 SCAS TESTS
- OH-58/TH-57 OPERATIONAL SUITABILITY
- FLY-BY-TUBE PROGRAM
- UTTAS SAS

Figure 1. Related Developments, 1967-1977

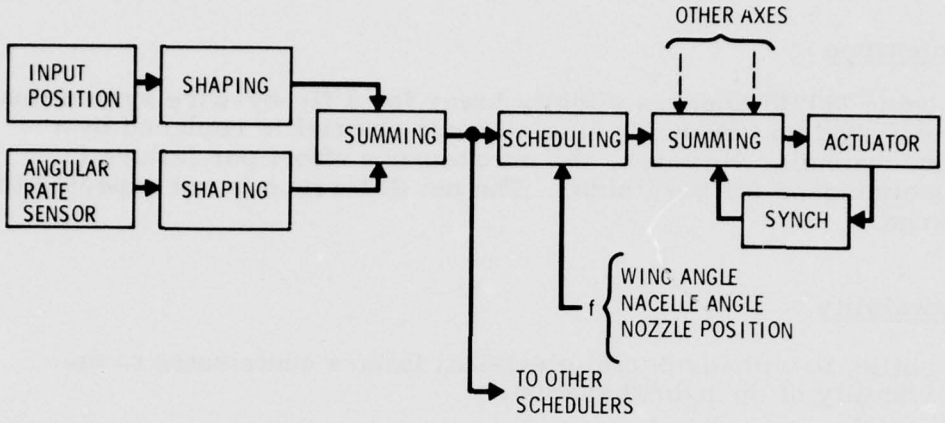


Figure 2. Basic Fluidics Control Channel

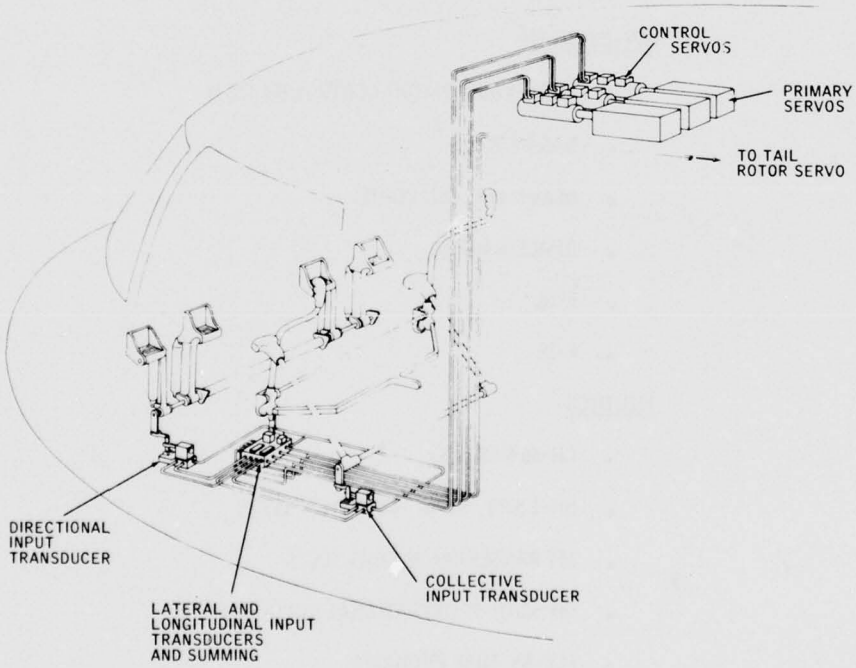


Figure 3. Fluidic Installation

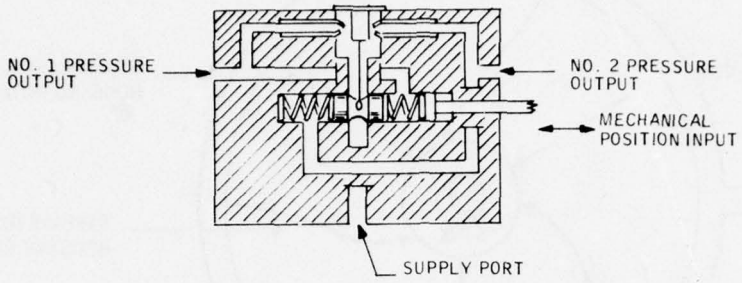


Figure 4. Mechanical Input Transducer

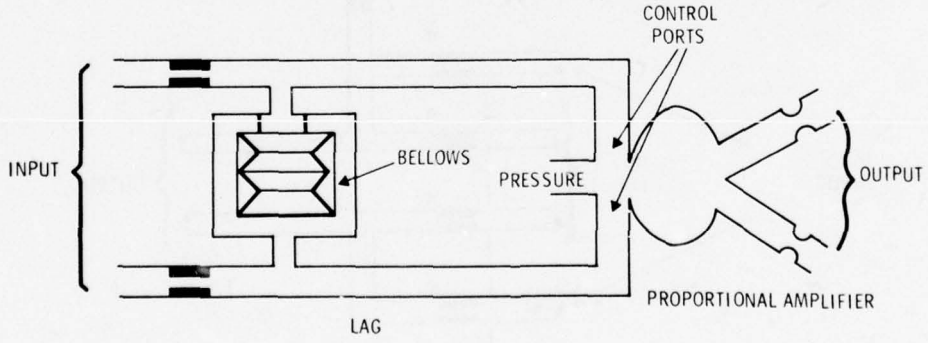


Figure 5. Low-Pass Shaping with Amplifier

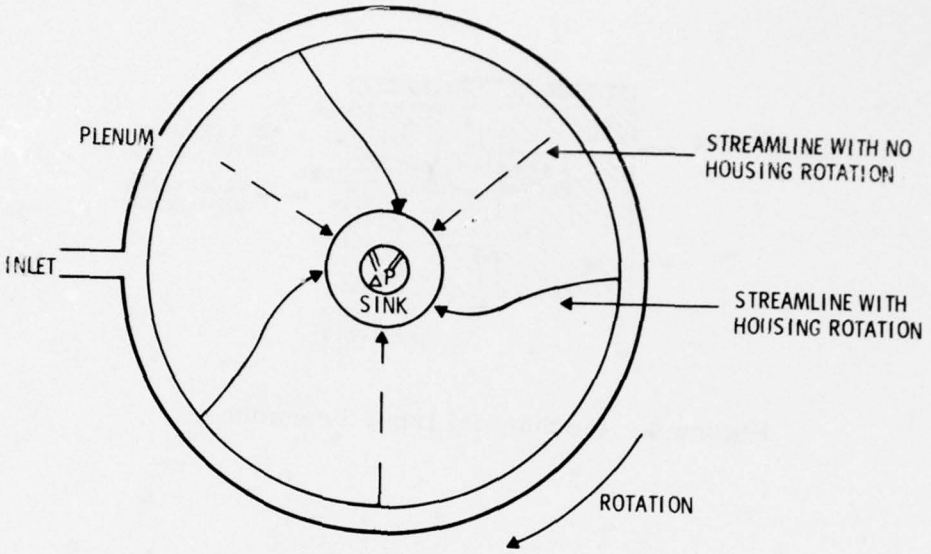


Figure 6. Vortex Rate Sensor

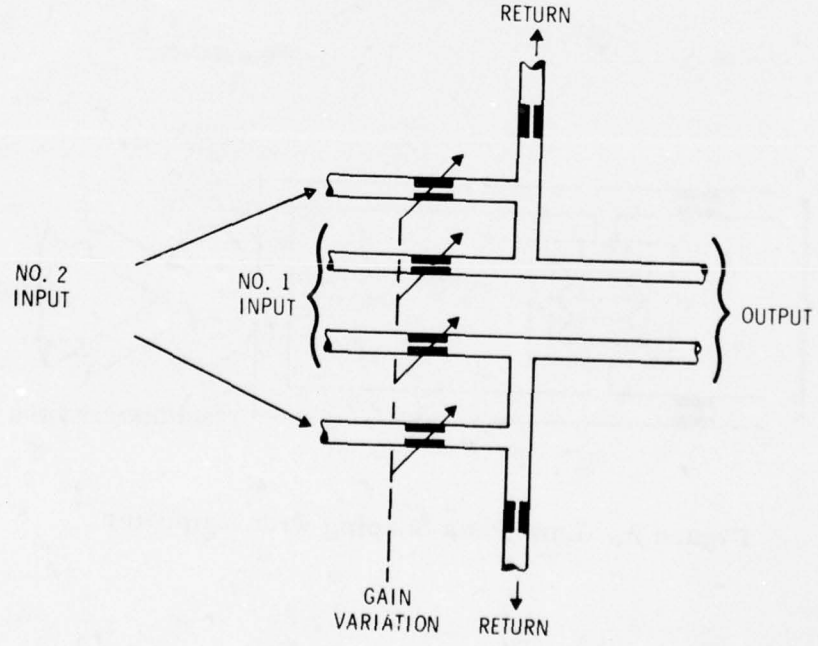


Figure 7. Fluidic Summing and Scheduling

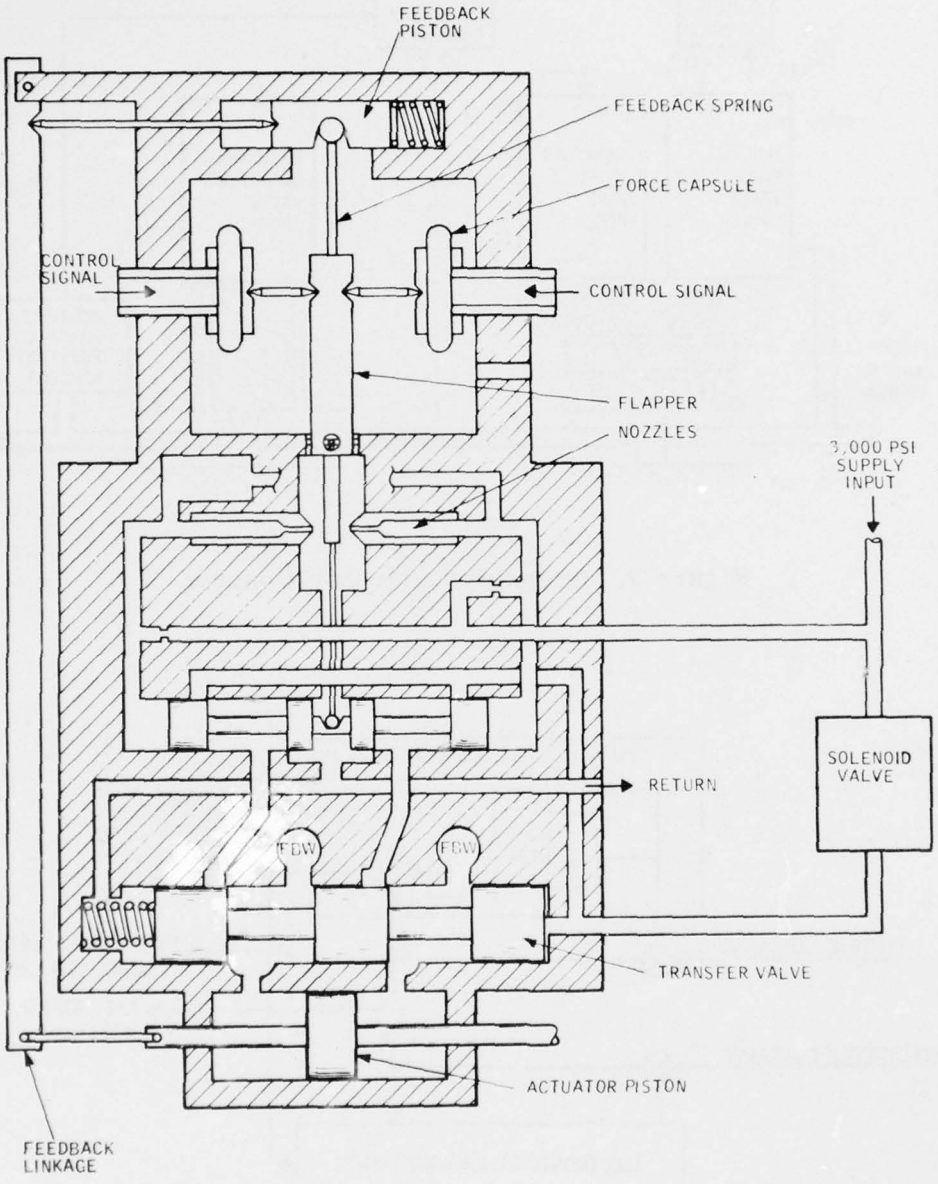


Figure 8. Fluidic Actuator

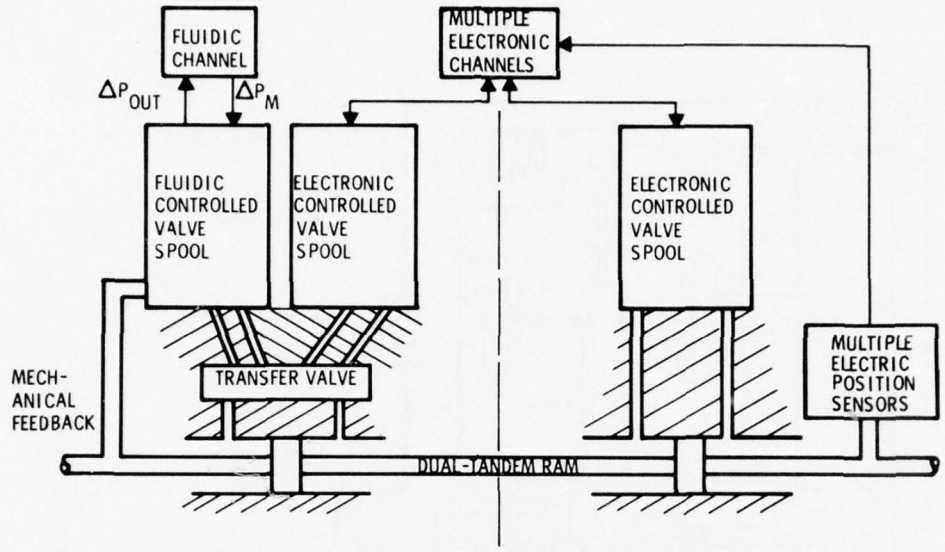


Figure 9. Integrated Actuator Concept

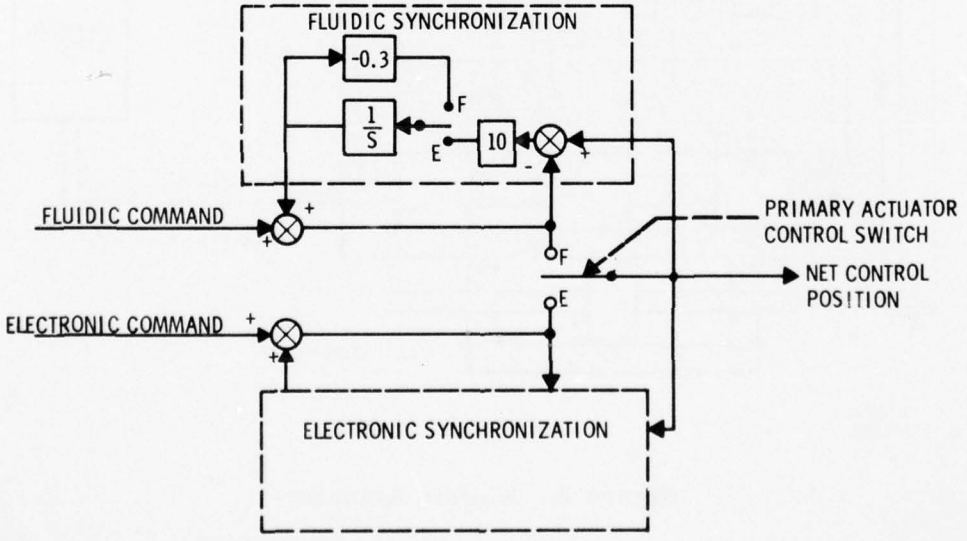
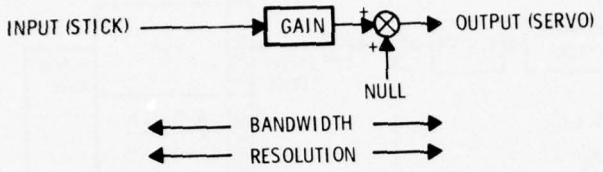


Figure 10. Channel Synchronization



PROPERTY	PRINCIPAL INFLUENCES	STATE OF ART
GAIN STABILITY	• FLUID VISCOSITY • FLOW RATE	20%, 40 to 220°F
NULL STABILITY	• FLUID VISCOSITY • FLOW RATE	10% OF FULL SCALE, 40 to 220°F
BANDWIDTH	• TRANSMISSION LINE GEOMETRY • FLUID VISCOSITY	> 5 Hz FOR 50 FT LINE T > 40°F MIL-H-5606
RESOLUTION	SERVO THRESHOLD	1 % FULL SCALE

Figure 11. Fluidic Channel Performance

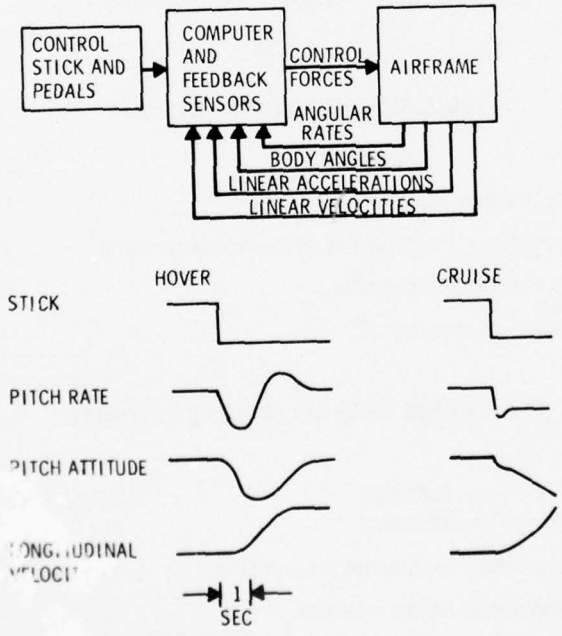


Figure 12. Electronic Augmentation

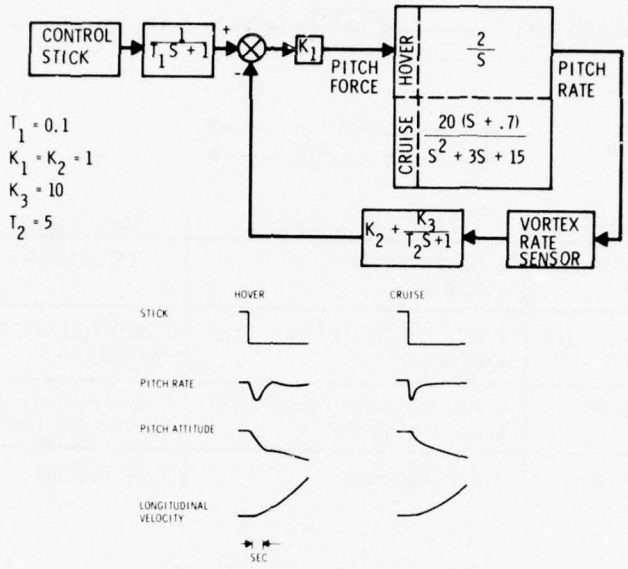


Figure 13. Fluidic Augmentation

FLUIDIC SYSTEM WEIGHT ESTIMATE

COMPONENT	WEIGHT (LB)
SENSORS, SUMMING AND SHAPING	10
HYDRAULIC PIPING (274 FEET OF LINE, FITTINGS, AND BRACKETS)	42
SECONDARY SERVOS (WEIGHT INCREASE)	10
ELECTRONICS FOR PREFLIGHT TEST	3
TOTAL	65

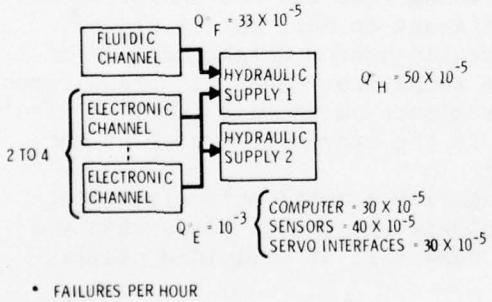
ELECTRONIC CHANNEL WEIGHT ESTIMATE

COMPONENT	WEIGHT (LB)
COMPUTER AND I/O ELECTRONICS	22
SENSORS (3 GYROS, 3 ACCELEROMETERS, 3 POSITION)	8
SECONDARY SERVOS (WEIGHT INCREASE)	10
TOTAL	40

Figure 14. Weight Estimates for Fluidic System and Comparable Electronic Channel

COMPONENT	FAILURE RATE PER COMPONENT, 10^5 HOURS	NUMBER PER SYSTEM	FAILURE RATE PER SYSTEM, 10^5 HOURS
MECHANICAL INPUT TRANSDUCER	0.5	5	2.50
JUNCTION BLOCK	0.75	4	3.00
TRANSMISSION LINE	0.15	8	1.20
SECONDARY SERVO	5.0	4	20.0
VORTEX RATE SENSOR	0.10	3	0.30
FLOW CONTROL VALVE	2.0	1	2.00
GAIN SCHEDULER	1.0	4	4.00
		TOTAL:	33.0

Figure 15. Fluidic System Failure Rate Estimate



• FAILURES PER HOUR

Figure 16. Redundancy Configurations

	MTBF (HOURS)	FAILURE PROBABILITY, ONE-HOUR FLIGHT	
		MISSION	SAFETY
DUAL ELECTRONICS*	300	1.1×10^{-3}	38×10^{-8}
TRIPLE ELECTRONICS*	231	10^{-3}	25×10^{-8}
QUAD ELECTRONICS	188	10^{-3}	25×10^{-8}

*95% TEST COVERAGE

Figure 17. Comparative Reliabilities (Hybrid Alternatives)

DISCUSSION

Charles Abrams: When one flies using the fluidic system, does one have limited motion side arm control?

Russel Hendrick: Although one of these has not been built, we don't see any reason why it cannot be built. Now as far as limited motion, I presume you mean a force stick with imperceptible motion. Here again, because our pickoffs are force dependent, I think that it could be designed although we haven't attempted to do that yet.

Robert Flynn: I didn't see wire weights for the electronic system in your weight chart. Was that buried in one of the other categories?

Hendrick: It wasn't in there at all, as a matter of fact.

Flynn: Well, that's not necessarily trivial. You'll often find that you have to go above minimum wire gage just for environmental reasons.

Hendrick: That's a good point. We had hoped that someday, with the multiplexed system, it would become a low percentage. That's my only excuse.

Duane McRuer: Either add the wire weight or take out the piping weight. Treat them fairly.

Dave Green: Did the piping weight include the fluid in the pipe?

Hendrick: Yes, it did. The weight of the fluid in the pipe ended up being small compared to the pipe weight. One thing that was not included, and I really don't know whether this was significant or not, but it did not include a potential increase in the hydraulic system weight because of the added fluidic flow requirements. We think that these flow requirements would be between one and two gallons per minute on the airplane. I wasn't sure whether to take a drastic increase in the hydraulic system or not.

Abrams: Russ, you say you've been flying with a multi-pole electrical power system. What is your provision relative to the displays when you lose all electrical power? Do you have some sort of a fluidic display backup?

Hendrick: No, we don't have fluidic displays, and this is obviously one of these total system kind of questions that you have to consider when you're selecting this kind of system. This concern also bears on the question of whether the handling qualities are adequate for a sufficiently large percentage of the missions. You have to ask yourself the same thing about the displays; namely, are there a high enough percentage of the missions that you could land without displays?

McRuer: One of the key points that you made, of course, was that this would be a good thing for those unexpected events that might occur. Now, as a proponent of both electronic and fluidic approaches, what unexpected events are you worried about in the electronic method.

Hendrick: I would include the common software error which is an unexpected event because if you had expected a design error, you wouldn't have designed it that way. It's a common error in any electronic system, and I shouldn't pick just on software. One common design error that is addressed in any kind of redundant system is that due to an unpredicted level of radiation. I think that we can successfully harden the electronic system against predicted levels of radiation. But we have to assume cable routing along with the (radiation) levels of the environment. If these were assumed wrong, they would become an unpredicted condition.

SESSION IV

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The Helicopter/Ship Dynamic-Interface Problem

– A New Approach –

By

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and

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Presented at
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April 1977

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ABSTRACT

A wind-tunnel test was conducted in the Boeing Vertol low-speed V/STOL tunnel to assess aerodynamic wake turbulence behind the superstructure of a 1/50-scale FF1052-class U.S. Navy frigate. The principal objective was to measure dynamic velocity data at a sufficient number of locations in the separated wake to define major areas of turbulence affecting helicopter operations aboard ship. The eventual goal of the ship wake program is to apply the results in piloted flight simulation work aimed at solving ship/helicopter dynamic-interface problems.

This paper documents the testing accomplished to map the turbulent wake and presents a sampling of the more interesting results gleaned from the test.

BACKGROUND

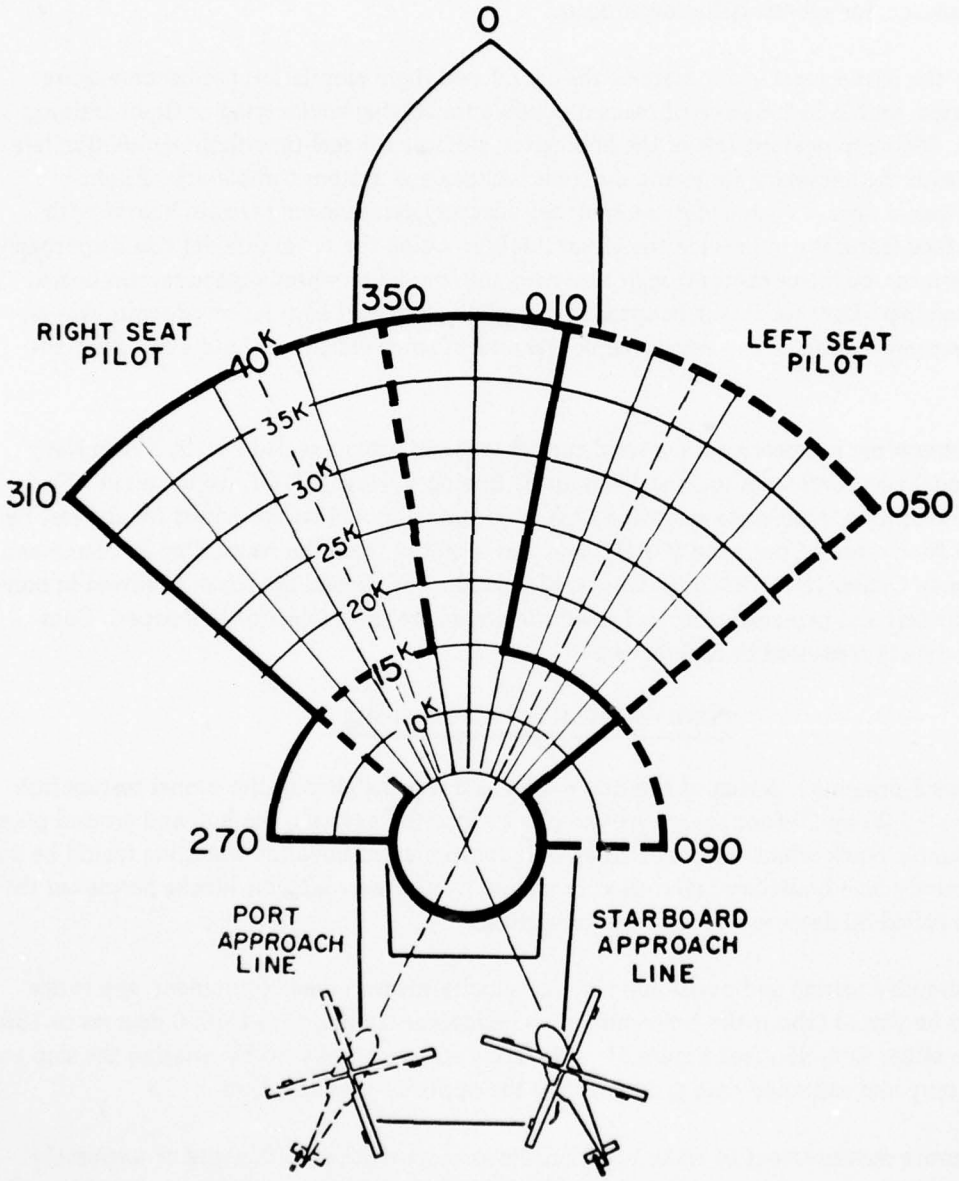
The United States Navy currently operates at least five different helicopter models from over 70 separate classes of nonaviation-type ships, such as destroyers, frigates, etc. Deployment of helicopters from the small helipad-size flight decks on these vessels creates a number of interesting handling qualities and performance problems not generally encountered when the aircraft are operated ashore.

Included among the more difficult of these dynamic-interface problems, as they are typically called, are the ship/aircraft limitations resulting from winds blowing across the deck and hull superstructure. These winds produce both unwanted turbulence in the landing area and crosswind/tailwind conditions affecting aircraft launch and recovery envelopes. When taken collectively with considerations of ship motion (and vessel configurational peculiarities that may exist in the area of the landing pad), the wind limitations define a dynamic-interface operating envelope which is unique for every helicopter/ship combination. A typical SH-2D launch and recovery wind-limitation envelope (Reference 1) for operations off a DE1052-class ship is shown in Figure 1. This is for daytime conditions with minor ship roll oscillations present. Restrictions become more severe with increased ship roll angles and reduced nighttime visibility, and depend on aircraft-system status such as ASE on/off, or on availability of ship landing aids, etc.

Traditionally, all dynamic-interface envelopes have been based on results of testing at sea. When a new helicopter is first flown aboard a nonaviation ship, extensive compatibility flight-testing is conducted with the ship under way to establish approach and departure envelopes for various wind and sea conditions. Because of the high costs of these tests and difficulty in obtaining the proper weather conditions, only a limited number of data points are obtained. Construction of the total diagram requires a large amount of engineering/pilot judgment and unless the critical conditions were flown, are usually conservative. In addition, only the most important testing has been accomplished so far. The largest number of tests, including those associated with new helicopters (such as the LAMPS Mark III vehicle) or ships not yet in service, remain to be done.

SH-2D Launch and Recovery Wind Limitations

DE-1052 CLASS SHIPS



DAY

0-5 DEGREE ROLL

STARBOARD —— SOLID LINE
PORT — — — — DASH LINE

Figure 1.

In early 1974, a multiphase exploratory program to develop and evaluate more cost-effective approaches toward dynamic-interface testing was jointly conceived by the Naval Air Systems Command and Boeing Vertol. The principal thrust of this program was to apply piloted flight simulation techniques as an adjunct to, or replacement for, complicated and expensive sea-trial testing. Potential exists for performing elements of this sea-trial work in a flight simulator, for substantially lower costs.

Over the past several years, state-of-the-art piloted flight simulation has become quite sophisticated, with a high degree of realism possible for solving engineering or flight training problems. Mathematical models of the helicopter, suitable for real-time flight simulation, are available with the necessary static and dynamic validity and system complexity. Flight simulator visual displays using closed-circuit television systems viewing terrain boards with scaled surface features can provide the visual fidelity. Using the terrain-model visual approach, ship motion can be introduced through a servoed ship model mounted on the terrain board. The missing ingredient for this helicopter/ship exploratory flight simulation program was an accurate representation of the aerodynamic wake turbulence existing behind a nonaviation-type ship.

To obtain the necessary data, a wind-tunnel program using a scaled FF1052-class Navy frigate model was conducted in June 1976 in the Boeing Vertol V/STOL wind tunnel. The 8-foot 10-inch-long, 1/50-scale waterline-type wind tunnel model was provided for the test by the Naval Air Systems Command (NASC) and was acquired from the Naval Ship Research and Development Center (NSRDC) in Bethesda, Maryland. The general approach followed in conducting the test and principal results gleaned therefrom are the subject of this paper. Complete test data is presented in Reference 2.

TEST EQUIPMENT AND MODEL

Figure 2 presents a sketch of the ship model as it was installed in the tunnel test section on an elevated 20-by-20-foot-square ground plane. Inserted between the hull and ground plane was an adapter block which ensured that all hull components above the waterline would be out of the ground-plane boundary layer velocity gradient. Alternate adapter blocks permitted the hull to be rolled 30 degrees right and left of vertical.

To simplify testing and positioning of the velocity-measurement equipment, the entire hull could be yawed (about the centerline of its helicopter landing pad) from 0 degrees to 180 degrees in either direction (see Figure 5). All testing was accomplished by rotating the ship to the right only and assuming data symmetry for the opposite yaw direction.

Accurate measurement of wake turbulence was accomplished with a grid of extremely sensitive split-film hot-wire anemometer probes (TSI Model 1080) attached to a movable rectangular rake as shown in Figures 3 and 4. Probe arrangement on the rake was carefully chosen on the basis of predicted location of vortices, and through application of smoke-flow-visualization techniques around the ship superstructure, to define the principal areas of turbulence in the lee of the hull.

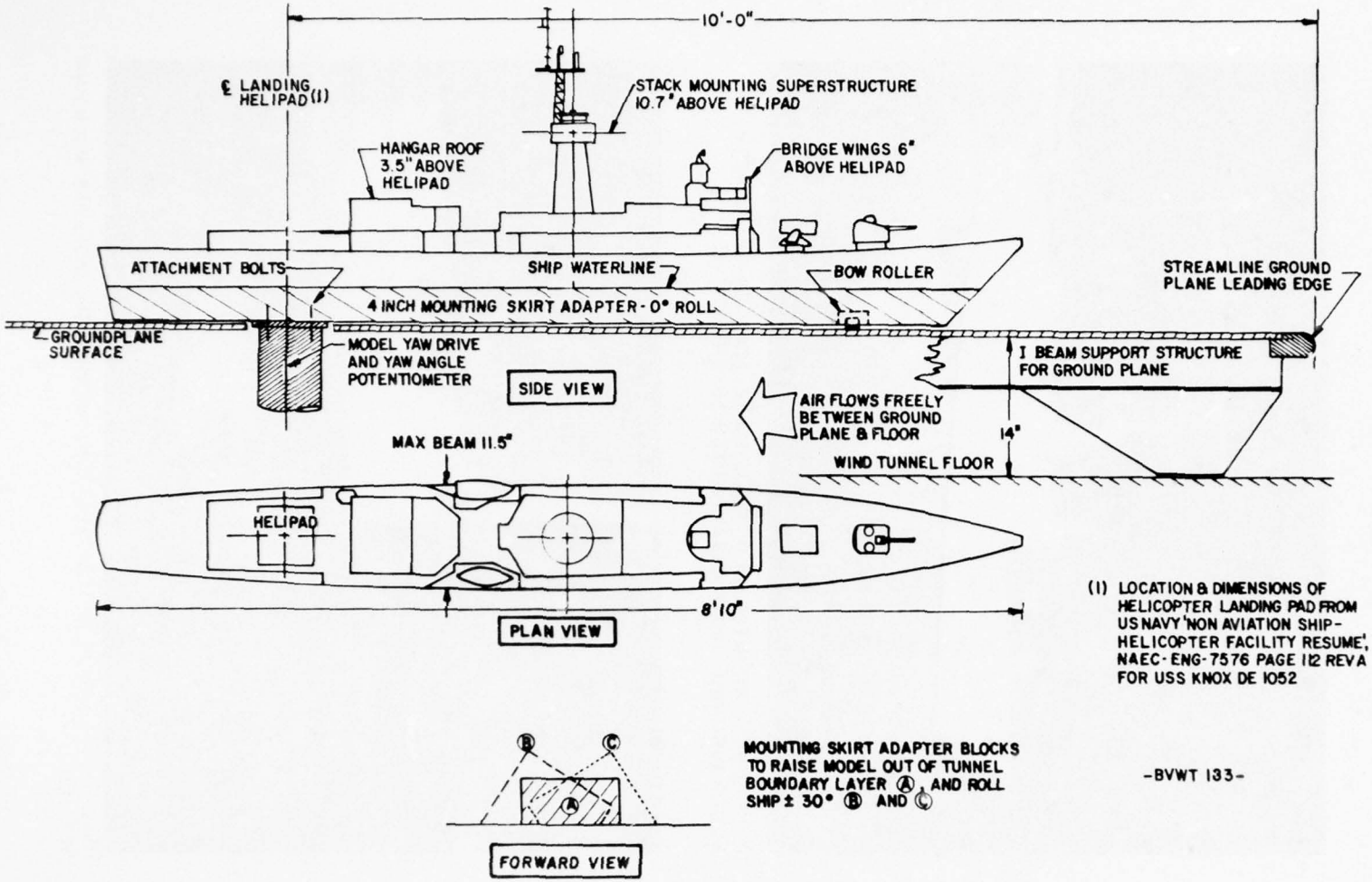
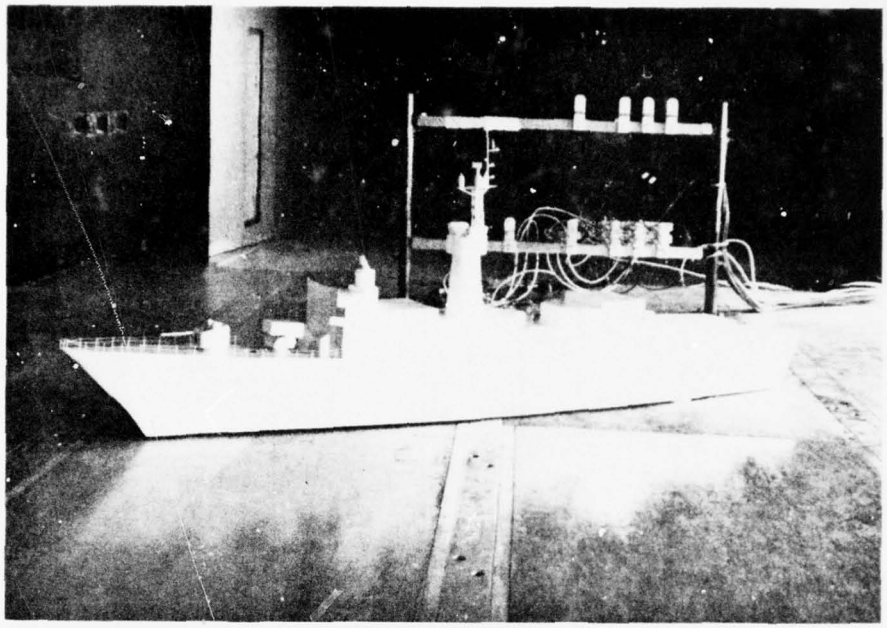
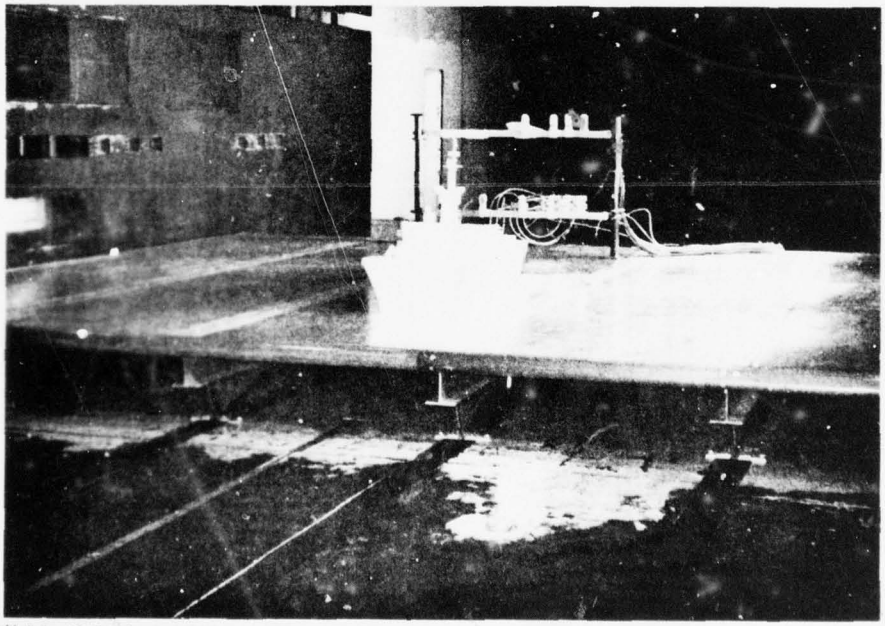


Figure 2. Wind Tunnel Ship Model Geometry – 1/50 Scale DE 1052 (FF1052) Showing Installation in Tunnel Test Section



DE 1052 HULL MOUNTED ON 0° ROLL ANGLE ADAPTER SKIRT WITH "LOWER INBOARD" PROBE ARRAY (UNITS 1 THRU 7) ACTIVE



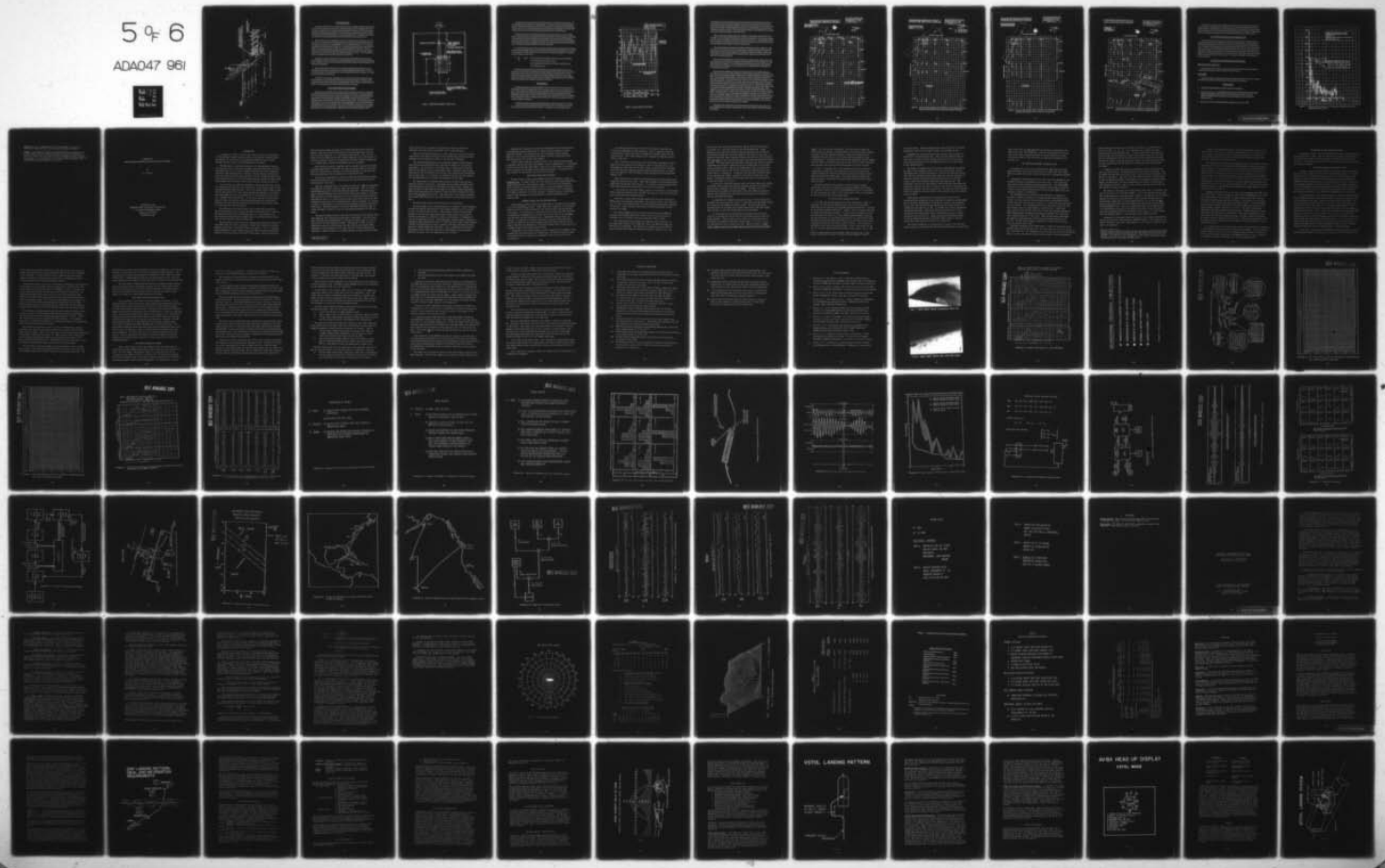
HULL INSTALLATION IN TEST SECTION SHOWING GROUND PLANE MOUNTING DETAILS

Figure 3. Ship Aerodynamic Wake Turbulence Test — BVWT 183

AD-A047 961 NAVAL AIR SYSTEMS COMMAND WASHINGTON D C F/G 1/3
PROCEEDINGS OF NAVY/NASA VSTOL FLYING QUALITIES WORKSHOP, HELD --ETC(U)
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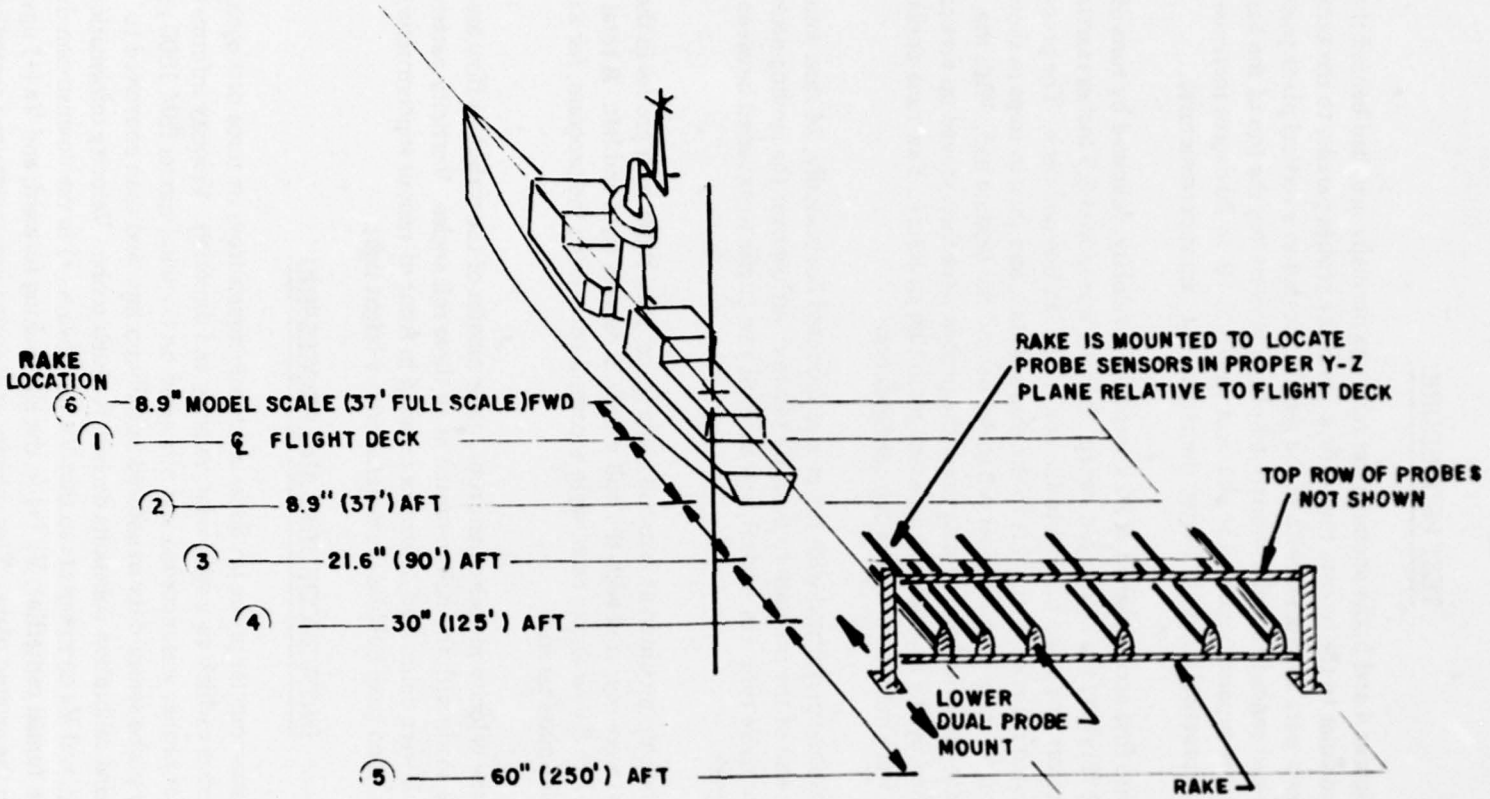


Figure 4. Anemometer Rake Positioning

TEST PROCEDURE

As shown in Figures 4 and 5, the anemometer rake was normally installed behind the ship and oriented perpendicular to the remote tunnel flow, with the probes parallel to the tunnel centerline. Initial tests were conducted with probe sensors located in a vertical plane passing through the landing-pad centerline and in horizontal planes intersecting the top of the hangar roof and forward-bridge superstructure. The ship was yawed in 10- to 20-degree increments to the right as far as was practical (without having the sensors hit ship superstructure).

Yaw sweeps were first accomplished at 20 knots tunnel velocity, followed by runs of 35 and 45 knots. After finishing the high-speed sweep, the rake was moved 8.9 inches rearward to position probe sensors in a plane parallel to the end of the landing-pad deck. The process was repeated by moving the rake further aft to the ship's fantail, and then in steps as shown in Figure 4 to a location 60 inches (or 250 feet full scale) behind the landing pad. With the hangar-roof and bridge-plane turbulence measured, the probes were then moved up vertically to check vorticity shed by the mast and its gas-stack mounting structure. Yaw runs similar to those just described were made with this probe configuration.

In addition to testing performed with the probes mounted horizontally, 24 runs were accomplished at the end of the program to evaluate tailwind airflow over the landing-deck area. Probe orientation for these runs was vertical, and the hull yaw angles were varied between 120 degrees and 180 degrees.

All runs with the ship mounted at zero roll angle (except for those with probes in the gas-stack/mast plane) were repeated with the hull rolled 30 degrees right and left. A total of 137 data runs, with 7 to 8 yaw angles each, were accomplished during the program, for a grand total of over 950 test points taken.

In addition to the velocity-measurement runs, color movies of the turbulent-flow areas behind the ship were made with the hull mounted at all three roll angles. Vorticity patterns downwind of the hull were delineated by smoke released in front of various superstructure elements, or by helium-filled soap bubbles illuminated with a bright light.

DATA RECORDING AND PROCESSING

Each hot-wire anemometer probe produces electronic signals from its three orthogonally oriented split-film sensors which vary with wind velocity and direction. Velocity information from the anemometer probes was recorded and processed on the wind-tunnel IBM 1800 computing system. Raw probe-sensor data was stored initially on tape and then converted to engineering units, using calibration constants derived for each probe. Velocity information was resolved into Vx, Vy, and Vz components so that Vx was always (+) in the downstream direction parallel with the tunnel centerline; Vy (+) to the left looking forward; and Vz (+) upward and perpendicular to the ground plane. This velocity convention was maintained regardless of ship heading, in order to simplify later application of the data in flight simulation work.

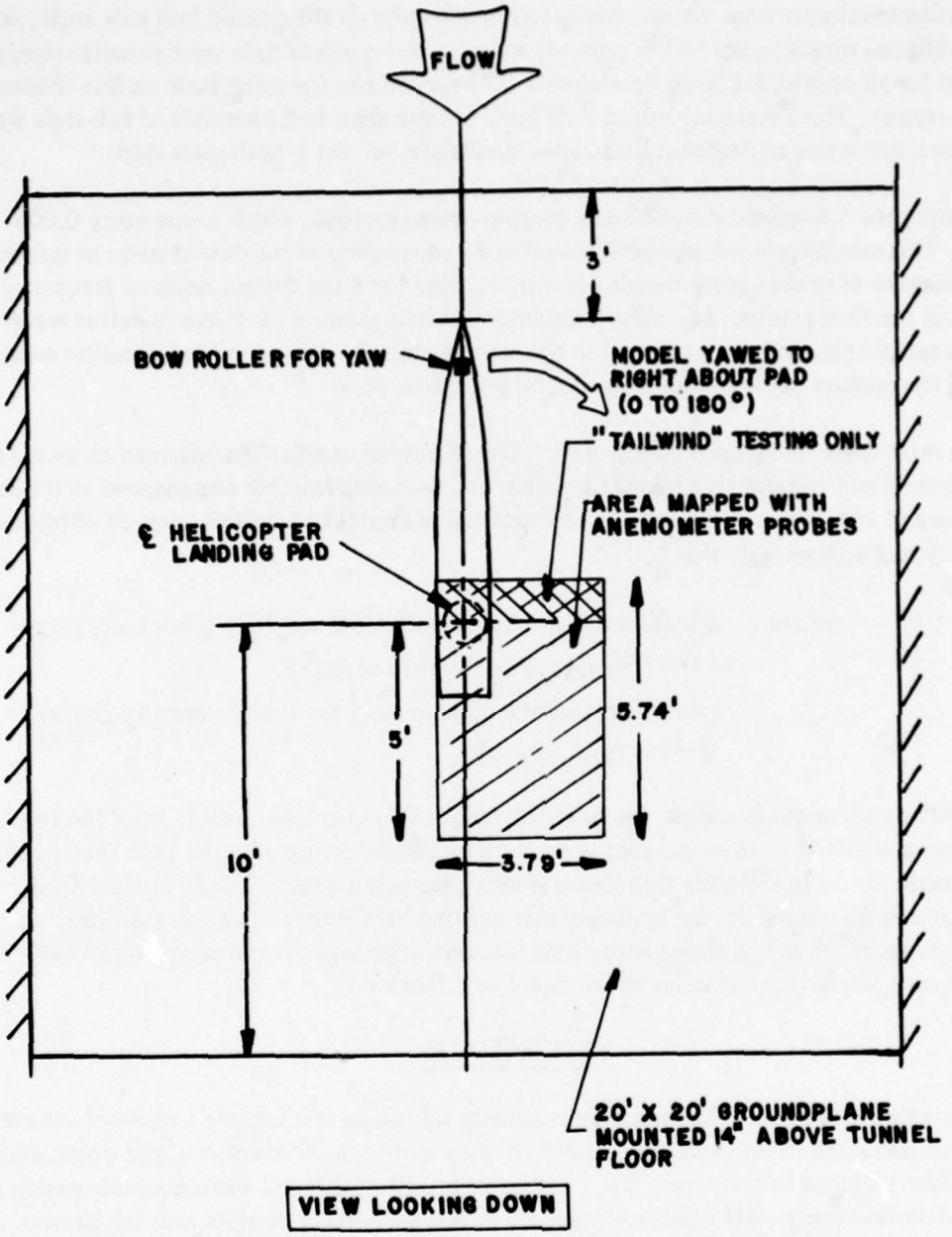


Figure 5. Ship Model Installation in Wind Tunnel

Dynamic-velocity data was recorded after first setting up the desired hull yaw angle, and then stabilizing tunnel speed on the nominal value. 1.6 seconds of data were simultaneously recorded for all probes, followed by a shorter 0.75-second run for quick-look on-line checks of the test results. The 1.6-second model-data burst is equivalent to 80 seconds of full-scale wake turbulence, according to Strouhal scaling-law similarities for the 1/50th-scale ship.

During the 1.6-second run, 262 data samples were recorded, which is one every 0.006 second. This sample rate was primarily dictated by constraints of the data system, as influenced by the number of probe-sensor signals being multiplexed and the desired range of frequency content in the final results. Assuming a minimum of four samples per cycle to define waveform, the data-sample rate and run time used in the wake-turbulence test permitted accurate measurement of frequencies between 0.625 Hz and 50 Hz, model scale.

To refer these frequencies to full-scale values, Strouhal number was assumed to be the same for the model and full-size ship (since the minimum Reynolds Number experienced in the model test exceeded 10^3, which is the criterion for constancy established in Reference 3). Strouhal frequency-scaling laws state that:

$$S = \frac{fh}{V}$$

where: S is Strouhal number (usually constant for a given body shape)
f is the frequency of the shed vorticity
h is a characteristic dimension of the body (normally width)
V is the flow velocity.

Based on these relationships, the full-scale range of frequencies possible from the test results can be derived from model-frequency data by simply dividing by the scale factor (50:1). This division results in full-scale turbulence frequencies ranging from 0.0125 Hz to 1.0 Hz, which is more than adequate for application in existing helicopter simulation math models. Scaling the recorded model time history data for simulation work requires only that the 0.006-second time between data samples be increased to 0.3 second.

TEST RESULTS

The principal results of the wake-turbulence wind-tunnel test include a series of velocity time-histories recorded (in engineering units) on magnetic tape for every run, test point, and probe. Also included in Reference 2 is a computer-printout listing of the same information processed to derive steady-state mean and standard-deviation velocity components for all runs. No attempt has been made to analyze the test results in any comprehensive depth at the present time for this paper. Rather, the data have been reviewed for validity and samples of the more interesting results are included.

A typical time-history representing the longitudinal Vx velocity component for a single probe located 125 feet (full scale) directly behind the left corner of the hangar roof is shown in the computer-drawn plot illustrated in Figure 6. In addition to the time-history trace,

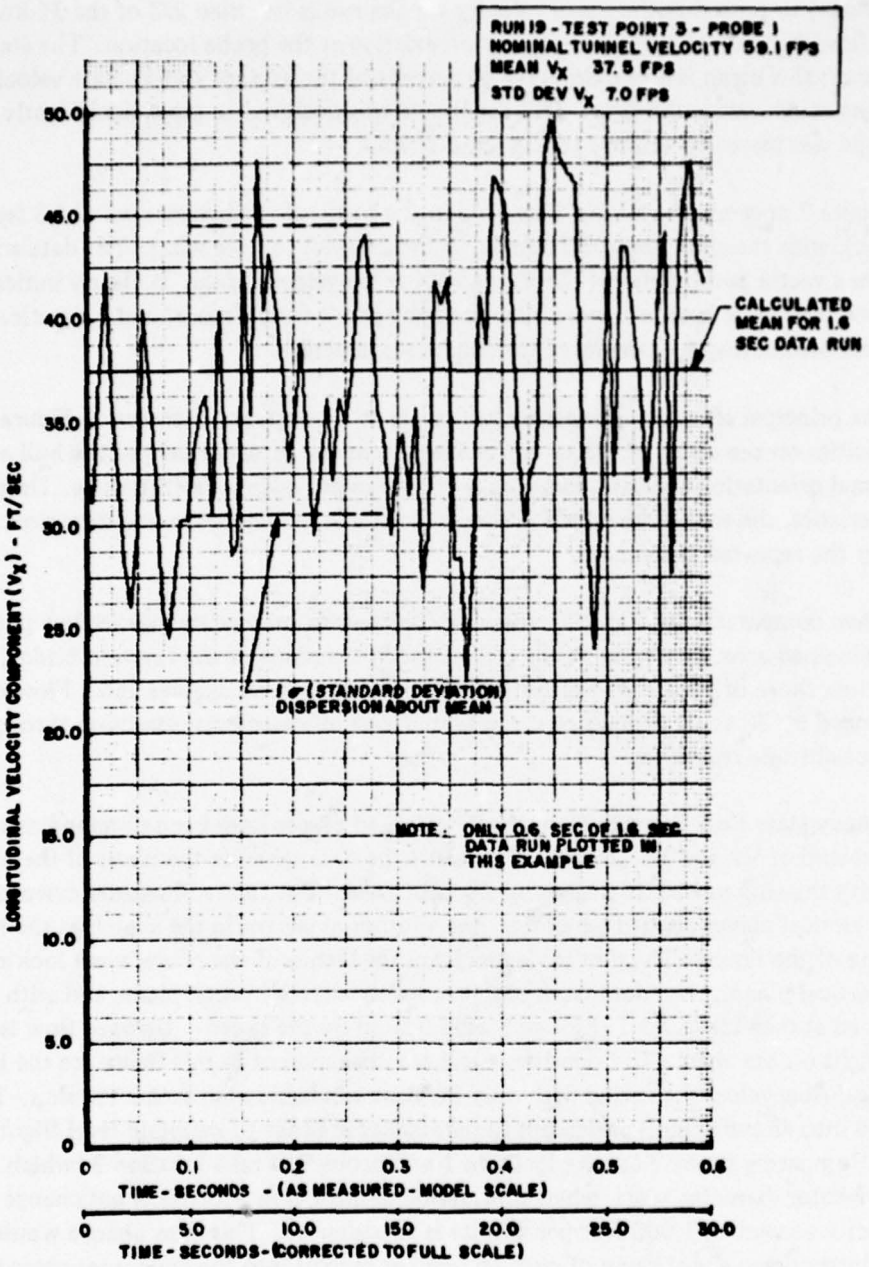


Figure 6. Typical Velocity Time History

the calculated mean and standard-deviation values are shown for the particular test point. It is interesting to note that the mean velocity for the run is less than 2/3 of the 35-knot free-stream flow, because of turbulent separation existing at the probe location. The standard deviation about this mean is approximately 20 percent of the average steady-state velocity level, indicating roughness in the flow. This roughness was observed to grow significantly as the ship yaw angle was increased relative to the remote wind.

Figure 7 presents the steady flow field in the plane of the hangar roof (14.6 feet above the deck), with the ship yawed 30 degrees to the 20-knot remote wind. The data was constructed from a vector summation of the Vx and Vy mean-velocity data. It clearly indicates a skewing of the flow, as it becomes more aligned to the ship's fore/aft axis, and a significant velocity reduction behind major elements of the ship superstructure.

The principal effects of increasing yaw angle to 50 degrees are shown in Figure 8. Typical velocities on the order of 1/3 or less of free steam are apparent behind the hull and their directional orientation indicates large areas of swirling or eddying in the wake. Despite these characteristics, the steady flow field is amazingly stable in magnitude and direction, as indicated by the repeated test points.

When compared with Figure 7, Figure 9 illustrates a marked change in flow pattern over the landing-pad area. In Figure 9, the probes are in the plane of the forward bridge, 11.4 feet higher than those of Figure 7. For both cases, the ship is at 30 degrees yaw. Flow direction has changed by 30 to 40 degrees over the fantail area in a clockwise direction through this 11.4-foot altitude reduction.

Steady-state flow patterns in vertically oriented planes have been obtained through a vectorial sum of Vx and Vz. Figure 10 presents the data taken in the plane of the hangar roof, again with the ship yawed 30 degrees in 20-knot wind. The figure illustrates orientation of the flow in vertical planes aligned parallel to one another as shown in the sketch at the bottom right side of the figure. The plot is viewed from the left, as if the reader were looking at a series of six vertical planes, with data from one probe only shown in each plane, and with the probe positioned at rake locations 1 through 5 as indicated by the sketch. Upward flow is directed to the right on the chart. The significant test results apparent in this figure are the large changes in vertical-flow velocity existing with only 20-knot winds blowing across the ship. These translate into aircraft climb or descent requirements in order to maintain level flight near the vessel. Comparing probe 7 at rake location 1 and probe 9 at rake location 2 (which are approximately 1 rotor diameter apart, when considering LAMPS-size aricraft), a net change in vertical velocity exceeding 1,000 feet per minute is experienced. This flow change would be equivalent to introducing a gust-ramp of over 16 feet per second into the helicopter rotor system, if the aircraft were flown behind the hull with the rotor at hangar-top height. Some other approach path to the ship which avoids this area is desirable.

Data taken at 35 and 45 knots shows flow directions virtually identical to those at 20 knots, indicating that, at least for mean velocity, only one set of data is required with remote wind scaling.

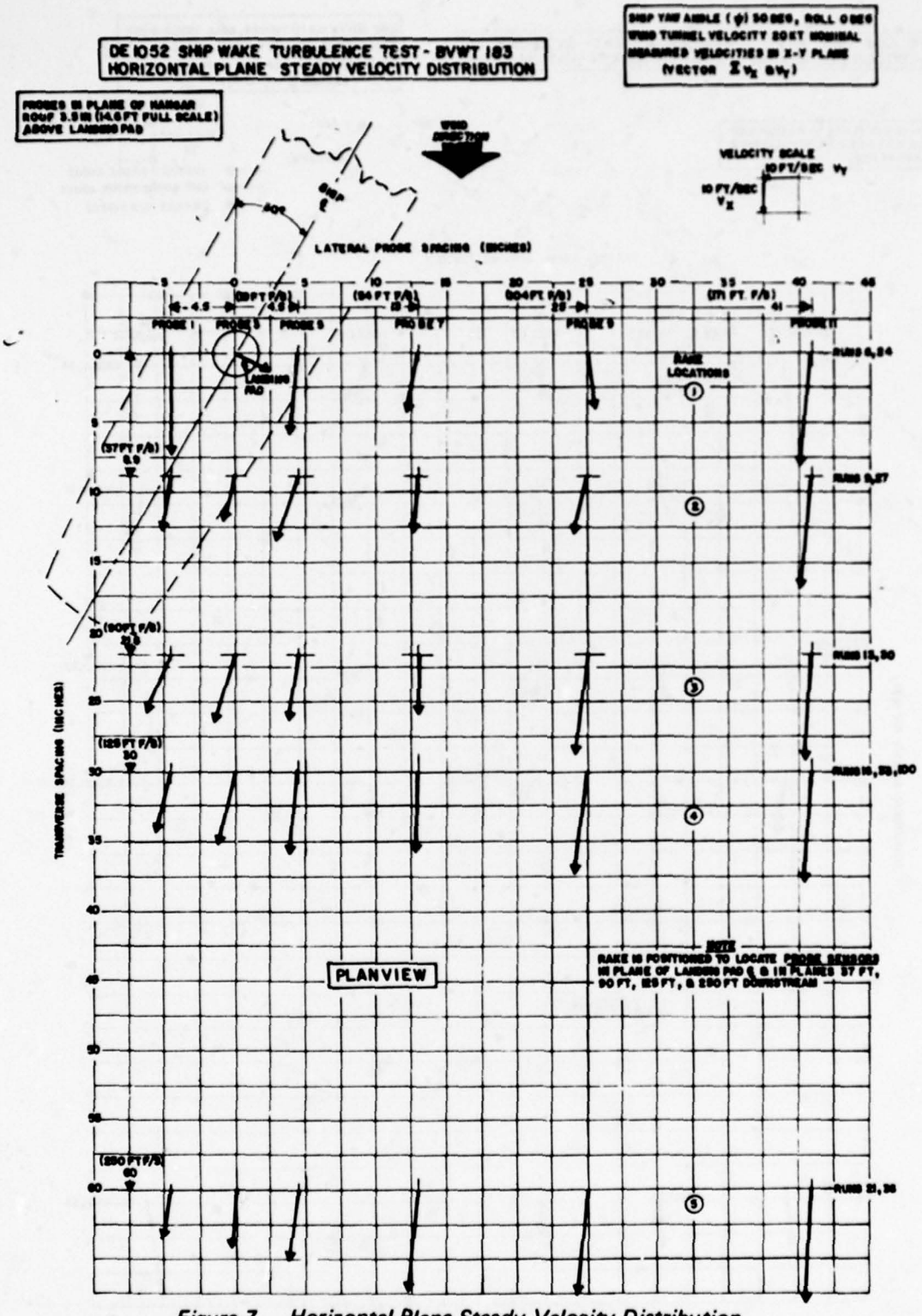


Figure 7. Horizontal Plane Steady Velocity Distribution

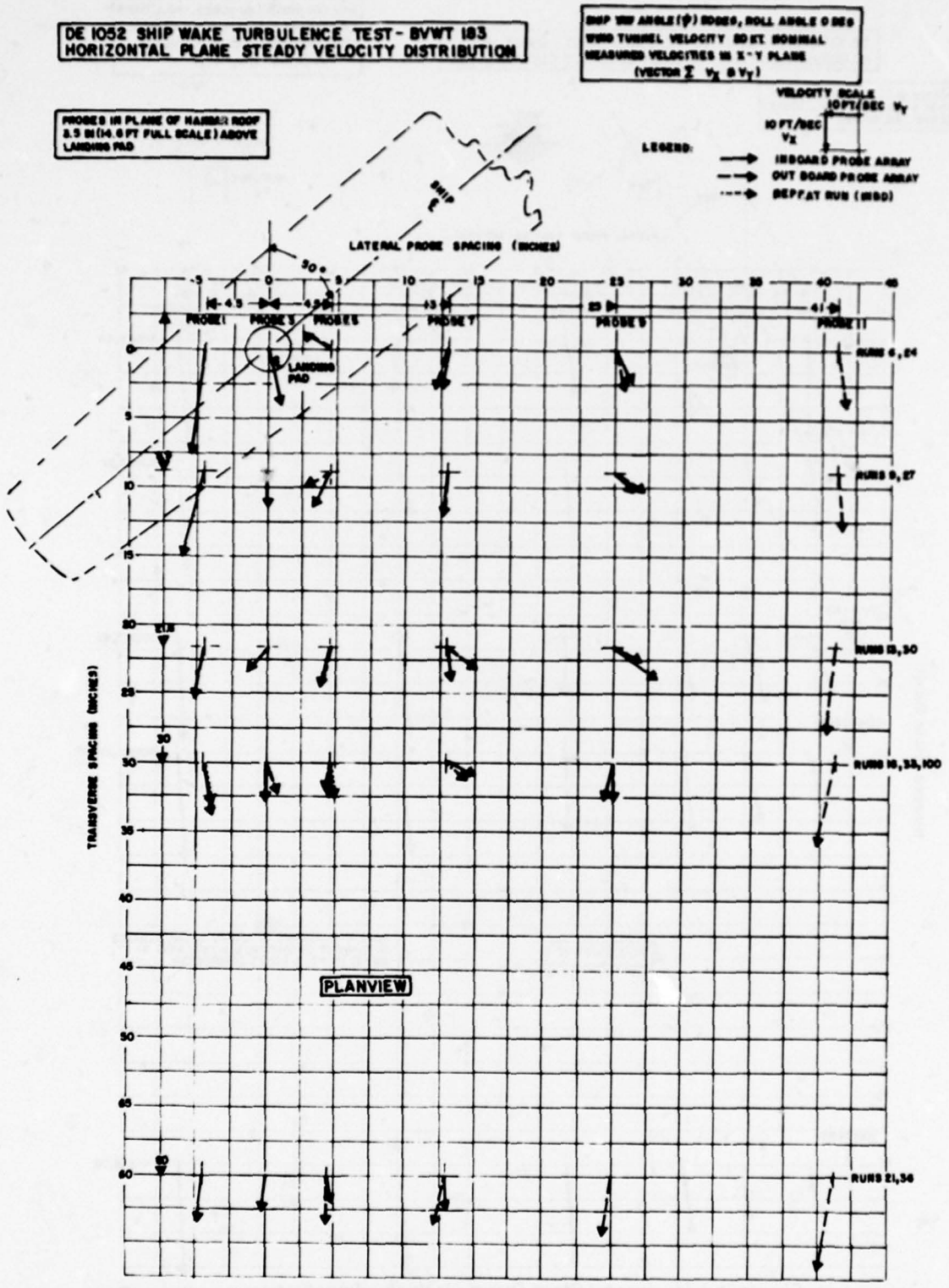


Figure 8. Horizontal Plane Steady Velocity Distribution at 50 Degrees Ship Yaw Angle and 20 Knots Wind Tunnel Velocity at Hangar Top Height

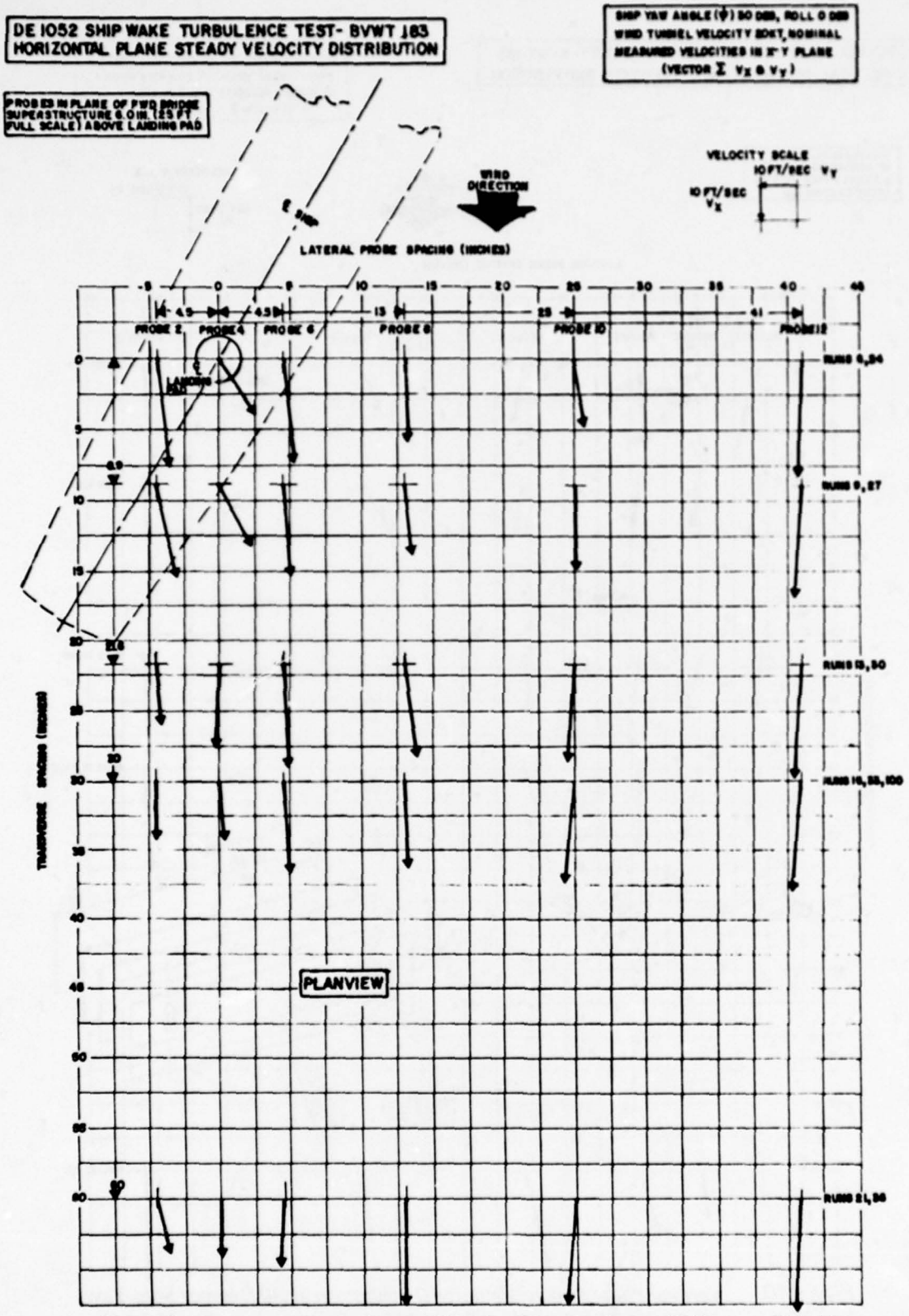


Figure 9. Horizontal Plane Steady Velocity Distribution at 30 Degrees Ship Yaw Angle and 20 Knots Wind Tunnel Velocity at Bridge Height

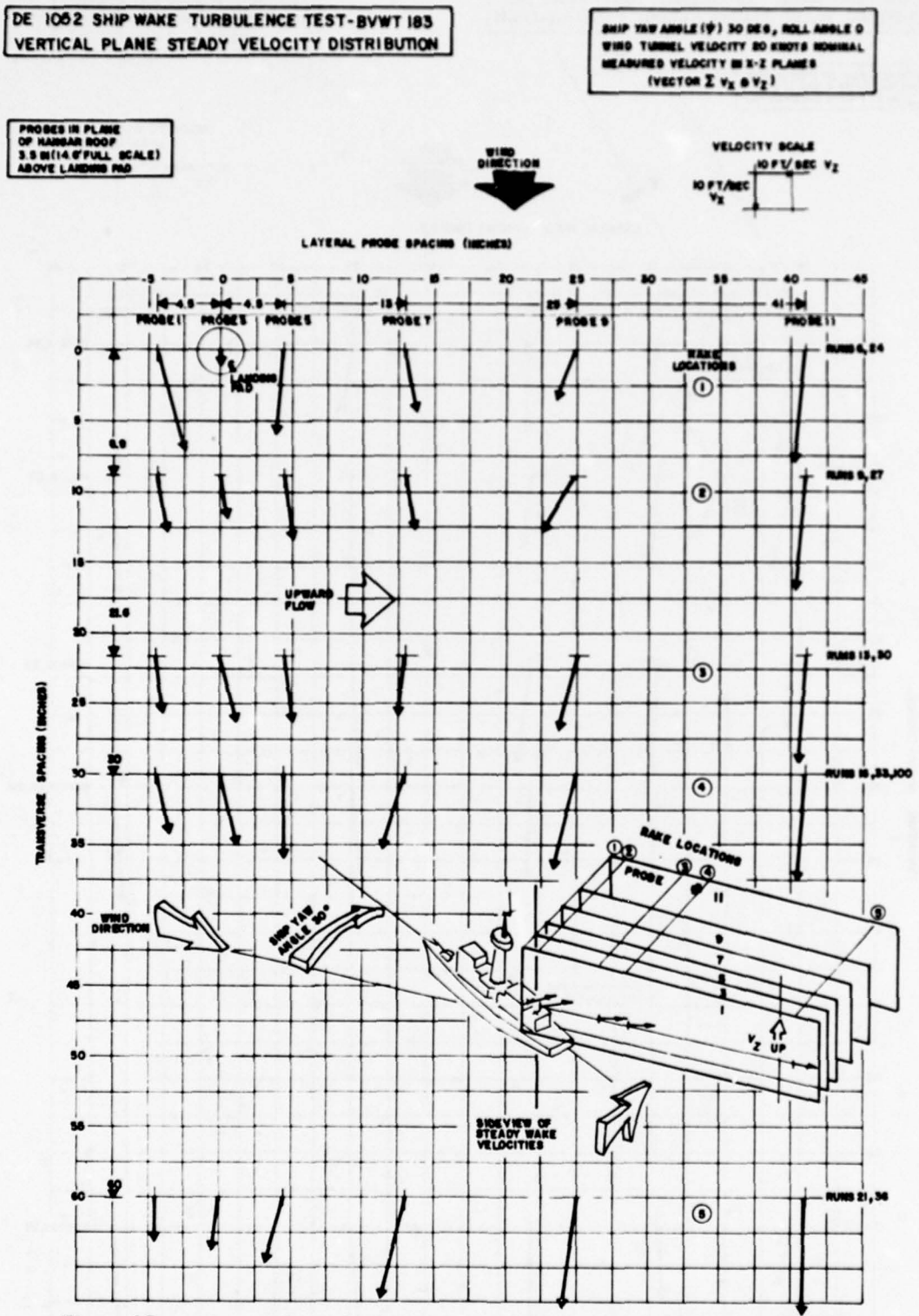


Figure 10. Vertical Plane Steady Velocity Distribution at 30 Degrees Ship Yaw Angle and 20 Knots Wind Tunnel Velocity at Hangar Top Height

The frequency content of the turbulence was observed on-line during the program to assure adequacy of the sampling rate. A sample of data for Vx is shown in Figure 11 for the noted conditions. Low-frequency-velocity amplitudes are high, approaching 5 feet per second, which is close to 10 percent of the remote velocity and 35 percent of the mean at this location. Most of the significant turbulent energy is below 20 Hz model scale or 0.4 Hz full scale.

DATA APPROACHES FOR FLIGHT SIMULATION

At the present time, two approaches toward using the wind tunnel turbulence data for future flight simulation work appear viable. The first involves application of the steady-state (mean) velocity information in concert with some type of computed random-turbulence function. The second (and somewhat more cumbersome) approach would be to store the Strouhal-scaled, time-history, dynamic-velocity data points directly in the computer, after first performing a time correlation of information from the various probes. Selection of the required data application methodology depends upon the results of further data analysis, including turbulence power-spectra calculations for each data point. If the spectra are similar, the first approach would be superior.

ADDITIONAL APPLICATION OF TEST RESULTS

Start-Up/Shut-Down Limitations

The turbulence data can also be used in conjunction with rotor-blade flapping analyses to estimate wind limitations during rotor start-up and shut-down.

V/STOL/RPV

Approaches similar to those being developed for helicopter launch and recovery envelopes can be used for all types of V/STOL aircraft and remotely piloted vehicles.

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2. Garnett, Theodore S., Jr., INVESTIGATION TO STUDY THE AERODYNAMIC SHIP WAKE TURBULENCE GENERATED BY AN FF1052 FRIGATE, Contract No. N00019-75C-0493, Naval Air Systems Command, Washington, DC, AIR-530112, December 1976.

3. Hoerner, S.F., FLUID DYNAMIC DRAG, published by the author, 1958.

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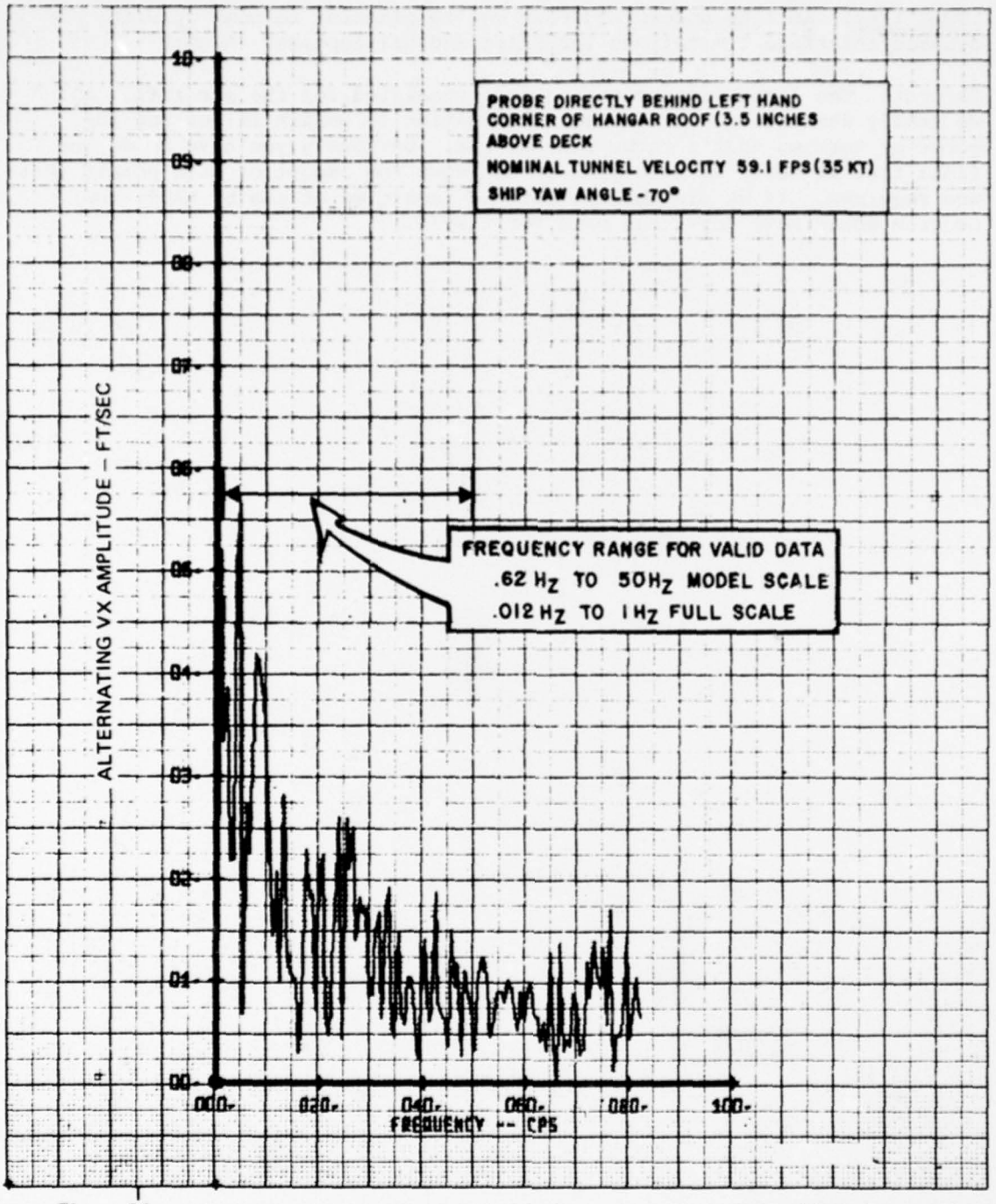


Figure 11. Ship Wake Velocity Survey, Vx Vs. Frequency, Probe Behind Left Corner of Hangar Roof, Run 19 TP 5

LTCOL Iles: Am I to understand that you're planning to come up with dynamic interface limitations for ships and helicopters? Right?

Garnett: The limitations right now are specified for the aircraft. All we really want to do is to obtain information to assist in setting the scope of testing that's to be done at sea. Obviously you have to do the final test at sea. We just want to cut down the amount of data points that are required. If we are able to cut the task time at sea by half, the program would have more than paid for itself.

A SUMMARY OF
SHIP DECK MOTION DYNAMICS AS APPLIED TO VSTOL AIRCRAFT

by

A. E. Baitis

Presented at the
Navy/NASA VSTOL Flying Qualities Workshop
U.S. Naval Postgraduate School
Monterey, California
26-28 April 1977

INTRODUCTION

In operating a VSTOL or VTO aircraft from a ship at sea, the motions of the landing or takeoff platform serve as just one more complication to be faced by the pilot during his hyperactive stage when the aircraft changes from the airborne to shipborne mode or vice versa.

The deck motions contribute directly to the landing/takeoff task by requiring the pilot to maintain acceptable clearances between his aircraft, the moving deck, and the various topside features of our naval combatants. Indirectly, and perhaps equally important, the deck motions contribute to pilot work load by producing fluctuations in the air turbulence shed by the ship's superstructure. As both wind speeds and ship motions increase, these unpredictable wind turbulence loads on the aircraft increase in severity.

If we restrict our attention somewhat to relatively high speed or high lift capacity VSTOL aircraft, two simplications in the deck motions and the aircraft handling problems follow. First, the larger, heavier VSTOL aircraft will be less sensitive to wind turbulence loads and secondly, it is likely that these VSTOL aircraft will operate off or with relatively large ships (i.e., DD 963, LPD's and upwards). In this case, the ship or deck motions that are likely to interfere with aircraft operations are substantially different from deck motions experienced by the smaller non-aviation ships currently operating with helicopters.

The difference in the deck motions of the large ship type and the smaller non-aviation ships is that the large ships are much less likely to be affected by the local wind generated seas, i.e., shortcrested seas. The large ships tend instead to respond more to the longcrested swell waves that are not associated with the local wind.

The implications of this ship size related wave environment difference is that VSTOL ships are likely to exhibit a rather finely tuned ship response behavior with respect to selected speeds and headings. That is, relatively small adjustments in speed and/or course are likely to produce significant changes in the pitch and roll motions of these ships. Here the term pitch

implies both pitch angle and the pitch related responses such as vertical motions, velocities, accelerations and the related consequences of these vertical plane responses, i.e., slamming and deck wetness. The term roll implies the roll angle and the roll related responses such as the lateral or transverse motions, velocities, accelerations and their related consequences, i.e., sliding cargo, aircraft and equipment as well as people!

The preceding discussion regarding the wave systems that are most likely to produce operational difficulties was made to indicate that for our VSTOL ships the predicted deck responses in swells designated as longcrested seas are more appropriate than the responses in shortcrested seas.

The first two viewgraphs are shown to illustrate the difference between the pitch related ship motion limits and the roll related motion limits in shortcrested or storm seas.

The first viewgraph shows a view from the bridge of a 3000 ton destroyer* proceeding at the maximum possible speed into storm seas. This is clearly a pitch/slamming/wetness limited ship operating condition. The question at hand is what, if anything, can we do to either reduce such motions or to adjust VSTOL operations to allow operation at or near such pitch limited conditions. The answer to this is to either avoid such seas, build ships such as the low waterplane vessels that do not experience this level of response, or, finally, to adjust the operations to time the critical operations to occur when motion lulls occur. The last procedure is the only available alternative that is likely to become a reality in time for the upcoming generation of VSTOL aircraft.

The second viewgraph shows a view from the same ship a few instants later when excessive roll produced ship operational limitations. The picture was taken with the camera perpendicular to the deck and thus gives us a view in what we call the ship coordinate system. The question at hand is what if anything can we do to either reduce such ship motions or to adjust VSTOL operations to allow operations at or near such roll limited environmental conditions. Again the answer is to employ methods to reduce ship roll under

*USCG WHEC Mellon

these conditions or to develop lull prediction techniques that allow advantage to be taken of the inevitable lulls in ship responses.

The first of these techniques,i.e., roll reductions, will be discussed extensively in the latter portions of this presentation, whereas the latter technique will be touched on briefly in the next few viewgraphs.

The third viewgraph presents a time stepped sequence of ship motions and the associated environment that produced the motions of the previous photographs. The top graph in the figure shows as a function of time the observed wave height and the measured ship speed. Note that these extreme, shortcrested seas are actually very rare but their duration once encountered can be quite long. It is important to recognize that for the vast majority of time VSTOL ships are not going to be operating in such seas.

The second graph in viewgraph three presents wind direction and wave direction relative to the ship. Note here that the common assumption that wind direction and wave direction generally coincide is true. However, it should be borne in mind that for the majority of motion related operational difficulties encountered with VSTOLs on ships, the ship's motions will occur due to the non-wind related swell. Thus, generally, true wind and the waves that produce ship motions will not align as neatly as during this rare storm case.

The third graph presents wind direction and wind velocity.

The fourth graph in the viewgraph presents a "hindcast" of ship responses - vertical and lateral accelerations at the landing platform bulls-eye as well as roll and pitch during the storm. The responses, given in terms of the average of the one-third highest amplitudes, attain levels of $\pm$ 0.25g for vertical accelerations, $\pm$ 0.10g for lateral accelerations, $\pm$ 10 degrees of roll and $\pm$ 6 degrees of pitch. These magnitudes, although large, would not by themselves negate possible helicopter or VSTOL operations under these conditions. Instead, the associated true winds in excess of 45 knots would make aircraft landing or takeoff operations impossible. Thus, irrespective of the size or the amount of ship roll/pitch response or stabilization, such operations would be limited by true wind speed and not ship motions.

Viewgraph four presents in concise form the objectives of one Ship Motion or Seakeeping Research Program that is likely to have an impact on future VSTOL ship designs. The objectives of this ship design related program emphasize in five succinct phrases the stages involved in ship design that take ship motions or responses into account.

I don't intend to go into particular detail into the above areas except to acquaint you with the basic requirements in such a design effort. A colleague of mine in the field from CNA, LCDR S. Olsen will go into detail on the performance assessment and its place in the ship design process. The needs of the ship designer for operational limits will be discussed.

SHIP MOTION PREDICTION PROCEDURES

A block diagram of the current DTNSRDC ship motion program is given in viewgraph five. It shows briefly the steps employed in ship motion predictions. Input consists of hull lines below the water line and the load information. Output consists of transfer functions which in turn are employed along with our conceptual model of the seaway to get ship responses in all six degrees of freedom at any point in or near the ship. Predicted results are developed either in the frequency or the time domain as may be appropriate for a specific task.

FREQUENCY DOMAIN SHIP MOTION PREDICTIONS

These frequency domain results are summarized for any particular responses in our so-called RMS/T_{oe} tables. These tables then represent in a statistical sense the universe of ship responses in the selected mode that can possibly be attained. It is important to recognize that the statistical RMS responses are determined independently so that you can only use them to get the worst roll and pitch and acceleration and etc., combinations without regard to phasing. In addition it should be noted that our present frequency domain results are valid for the so-called earth coordinate system and thus do not give an accurate representation of the motion induced inertia forces acting on a VSTOL aircraft fully supported by the ship.

Viewgraphs six and seven present the roll responses for the DD963 in long-crested seas and shortcrested seas respectively. We consider that the range of possible ship roll responses are bounded by these two sets of sea representations.

We regard longcrested seas or swells as the type of seas that are essentially independent of the local wind. That is, there are seas with long continuous crests which have traveled from a distant storm into the operating area. These seas produce no roll responses in head seas and no pitch in beam seas.

Here I must point out that our naval architecture convention is out of phase with your aeronautical convention. That is, when the wind or sea approaches the ship's bow from directly ahead, we consider this to be head seas 180^{o}, when the wind/sea approaches the ship from the beam, we regard this as being 90^{o} or 270^{o}, and when wind/sea approaches from the stern the heading is 0^{o}.

Shortcrested seas in contrast to longcrested seas are the confused seas associated with the local winds. These seas approach the ship from directions $\pm 90^{o}$ about the dominant sea direction. In contrast to the longcrested seas these shortcrested seas produce pitch and roll at all headings.

I must point out that these RMS/T_{oe} tables will define for you the regions where large ship responses occur and will thus give you a statistical description of expected motion response levels.

There are of course many different applications for these statistical RMS/T_{oe} ship motion tables illustrated in our various reports, see references 1-5. In fact, the following paper on a ship performance assessment technique illustrates a rather important application of these statistical rms ship response data bases.

As a second example please note that the responses of the 3000 ton destroyer-like (FF1040) USCG cutter Mellon during a storm presented in viewgraph 3 were "hindcast" using the appropriate RMS/T_{oe} tables.

This second applications example was expanded into a comparison of the flight deck motions of this 3000 ton cutter, the 7800 ton DD963, and the 17,000 ton LPH (GUAM). The flight deck responses were calculated at locations where VSTOL might be reasonably expected to operate, i.e. the

bulls-eye for the cutter and the DD, and, the VL and STO starting point on the LPH, i.e., 103 feet forward of the aft perpendicular. These comparison ship response "hindcasts" were made assuming that the DD and the LPH would repeat the course and speeds of the cutter in the storm. It should be noted that these response hindcasts are valid only for the blackened time spans on the time axis where both ship speed and heading were held constant. The lines connecting the motion responses thus "connect visually" independent ship response conditions and are provided only to illustrate general response trends. Results are summarized in terms of significant roll and pitch as well as the vertical and lateral displacements of the flight decks in viewgraph 8. It must be noted that these response levels do not represent the highest responses in the given "steady-state-time spans." The highest response cycles within such spans may be greater by as much as a factor of 1.5 to 2.

At any rate, these shortcrested, storm sea flight deck motion results illustrate rather graphically that the smallest ship does not necessarily have the worst responses in all motion modes. From this in turn it follows that the judgment of which ship is best for VSTOL a/c operation does not rest solely on just the pitch and roll motions of the ship or even the available deck space.

A comparison for example of the pitch motions of these three ships indicates that they are rather similar in magnitude, with the cutter having the largest and the DD963 the smallest pitch. The pitch associated vertical motion of the decks on the other hand clearly shows the largest ship, the LPH, to have the largest (worst) vertical motion.

It should therefore be recognized that angular pitch motion by itself is a misleading indicator of ship motions when several ships are being compared. In fact, pitch is only valid as a crude indicator of the motion environment of the VSTOL aircraft when it - pitch - is used for the operations with a single ship type. Again, the use of "pitch motion response levels that produce operational difficulties on one ship

class" is or can be very misleading. This fact must be taken into account when you attempt to develop VSTOL aircraft control power margins intended to provide adequate handling or maneuvering capability to compensate for ship motions, or similarly when you attempt to apply a compensation* for the aircraft performance degredation due to a degree of pitch motion to different ship classes than the ones which 'produced' experimentally the motion performance degradations of the aircraft.

In fact, I recommend that a more thorough ship motion prediction study both in storms and in the "seas most likely to produce motion related problems for VSTOL" be performed for the entire range of ships that may be potential VSTOL ships. This study should establish the range of motions, velocities and accelerations of the critical flight deck locations.

Although conclusions with respect to wind and motion induced operational limitations of VSTOL can be readily deduced from the data of viewgraphs 3 and 8, as well as the GUAM/AV8A sea trials of reference 6, they are beyond the scope of this current work. We return therefore to the time domain ship motion predictions.

TIME DOMAIN SHIP MOTION PREDICTIONS

If or when the phasing between ship motion components or modes is important in a ship motion dependent task, you go to a time domain prediction of the responses to eliminate phasing uncertainties - inherent in the frequency domain predictions. However, this time history approach is rather time and cost consuming. To get around the economics of such ship motion/time history predictions, NAVAIR tasked DTNSRDC to develop, for use by industry, a ship motion data base for five nonaviation ships. This data base and the report describing it was sent out to your various companies and should be available in your libraries. The results are available to you free of charge at DTNSRDC. Free in the sense that the data is stored on magnetic disc packs that you can access, use, or copy

*That is compensations in the limiting flight envelopes due to ship motions such as the "X knots of relative wind per degree of pitch."

as you may desire. Reports describing this and similar work including experimental work are in the public domain and available to you.

Viewgraph nine presents predicted ship response time histories in longcrested and shortcrested seas. Note that roll exhibits beats or lulls that are rather obvious, whereas pitch and the vertical plane ship responses pose much less noticeable beats or lulls in both types of sea representations.

The figure illustrates that the forces or accelerations introduced by lateral plane responses such as roll are quite different in ship coordinates than in earth coordinates or the inertial reference system. This inertial coordinate system which references the ship responses to the earth vertical traveling at the speed of the ship is the basic system in which ship response expressions have been derived. The difference in the forces experienced in these different coordinates are important! When your aircraft is airborne, the inertial coordinates are appropriate, whereas when the aircraft is on the deck the ship coordinate system is appropriate to describe the forces imposed by the ship motions on the airframe.

These motion induced forces or accelerations (forces in ship coordinates) acting parallel to the ship deck or laterally are designated by F_L and forces perpendicular to the deck or vertical are designated as F_N. Note that the ship motion induced lateral inertia force F_L is substantial with peaks up to .18g. F_L follows roll in both longcrested and shortcrested seas. Whereas the lateral accelerations in earth coordinates are substantially smaller with peaks up to about .1g and certainly do not follow roll. These substantial differences between the earth referenced and ship referenced lateral forces or accelerations occur even though roll motions are rather mild.

The similar comparison of accelerations or forces in the vertical plane illustrates that earth and ship system accelerations are essentially

equal and in fact are even less than the lateral F_L accelerations for these rather mild roll conditions. Clearly, the reduction of roll and thus F_L will have a beneficial effect on the performance of various tasks such as STOL or VTOL from ships by reducing the probability of sliding, etc.

SHIP MOTION AND AIRCRAFT INTERFACE TRIALS

Viewgraph ten presents trial objectives for AV8A operations with GUAM and RALEIGH and for SH-2D Operations on a 1052 class ship, BOWEN. Results of these and similar trials are reported in references 6 through 9.

Viewgraphs 11 and 12 present trial results that corresponded to the roughest conditions of operations up to that time. It was noted that the vertical plane responses produced cancellations. The RALEIGH/AV8A interface trials (see reference 7) produced no significant ship motion related results because the seas were too mild and the BOWEN results are reported in detail in reference 8.

The GUAM/AV8A trials on the other hand reported in reference 6 produced a wealth of conslusions. Perhaps the most important of these results are associated with the ship motions that produced AV8A launch/recover operation cancellations or delays, i.e. pitch and pitch associated vertical motions. The unpredictability of bow attitudes in fact was the most frequent cause of launch delays or cancellations. Significant pitch motions of $\pm$ 0.5° were sufficient to limit the launching operations. AV8A launch/recovery operations were generally delayed when significant pitch ranged between $\pm$ 1.7° to $\pm$ 2.1°. AV8A launch/recovery operations were generally cancelled when significant pitch ranged between $\pm$ 2.1° to 2.8°. No AV8A launch/recovery operations occurred when significant pitch was greater than $\pm$ 2.8°!

Viewgraph 13 expands on the GUAM results - namely on the motions which produced cancellations and what we in the ship design community are attempting to do about it. This viewgraph also summarizes the times that the HARRIER spent on or over the deck during the critical stages in the launch/takeoff

sequence when ship responses most severely influenced or introduced forces on the aircraft, i.e., F_L, F_N. It is necessary now to define the events associated with these measured times. In case of the vertical landing, the aircraft event was initiated the instant the aircraft crossed over the deck and was terminated the instant the aircraft was fully supported by the deck. The vertical takeoff event was defined in exactly the reverse order from the vertical landing such that the event was initiated once the tires started to unload.

It should be noted that generally the takeoff events were much shorter than the landing events. Landings generally required about 20 seconds. This 20 second time span then has become the goal by which we hope to forecast ship motions in the future. That is, in our lull prediction work with China Lake we seek to develop a predictor that predicts ship responses, especially pitch, heave, vertical motion, velocity, acceleration, 20 seconds into the future with reasonable accuracy. That is, with a greater accuracy than the LSO and LSE now have in these predictions.

The scatter in the short or rolling takeoff event times is noticeably less than is the case for the aircraft takeoffs. It is very important to note that none of the events are longer than eight seconds.* This factor is very important because the inability to satisfactorily predict the bow attitude when the aircraft had reached their critical takeoff position was in fact the major cause of the cancellation of aircraft operations due to ship motions during the HARRIER/GUAM trials. Thus our minimum ship motion lull prediction goal is to significantly improve the reliability with which the bow attitude of the ship is predicted some 8 to 10 seconds in the future, i.e., 8-10 seconds after the LSO/LSE signals to initiate the rolling takeoff are given.

Viewgraph 14 illustrates clearly as did Col. Isle's movies yesterday that what we are trying to avoid during the HARRIER launches is the "seastrike," to use Mr. Nicholas's term, and, simultaneously, we are trying to develop a ship motion lull predictor.

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*Clearly catapult launched aircraft from carriers have a much less severe ship motion or bow attitude prediction task than the VSTOLs during unassisted STOL takeoffs. The reason for this difference is that catapult events are much shorter (i.e., from 1.9 to 3.7 seconds) and thus take a much smaller segment of the ship motion cycle than the STOL events.

Viewgraph 15 illustrates a typical aircraft event during a lull in the ship motions. The lull is particularly pronounced here in the roll motion. We, of course, must develop a lull predictor that gives us at least 8-10 second forecast into the future for pitch and pitch related responses and 20 second forecast in the future for roll.

This viewgraph illustrates an interesting feature of the GUAM trials that goes along the lines of the ramp-on-deck HARRIER launch technique presented by Mr. Nicholas, our UK representative from the Royal Aircraft Establishment. Note that the bow of the GUAM was trimmed up by one degree. This clearly biased the pitch response towards a bow up launch, and preserved, at least to some extent, the initial launch distance above the water for the HARRIER. Clearly, the use of even this small a trim up by the bow is beneficial for the STO launches. When we add to this ship operation technique an accurate prediction of bow position from the lull prediction work, I believe that a worthwhile improvement in the HARRIER launch capability in rough weather will be attained in the near future.

Viewgraph 16 presents this as the last of the viewgraphs that deals with lull predictions. Again this data was taken from the GUAM/AV8A trials in 72-73. The solid blue line represents the ship motion measure that occurred during the aircraft event previously defined. In this case we are looking at lulls in roll motions that occurred during 20 events. It was considered that the highest double amplitude of ship motion within the aircraft event would produce a control response by the pilot. The yellow hatched area represents the highest double amplitudes within a 10 ship motion cycle span before and after the actual aircraft event. Thus when these highest events are greater than the event double amplitude, the pilot evidently succeeded at landing during a relative ship motion lull. When the yellow and blue lines coincide, the pilot clearly has not succeeded in placing the event in a ship motion (roll) lull.

It is clear that for the worst event shown he was unsuccessful in locating a lull whereas for many of the other events he did succeed. In this connection we again hope to improve his lull locating box-score with the lull predictor. It may be of interest to note that these HARRIER pilots were more successful in locating lulls than SH2-D pilots were during the BOWEN trials.

DEVELOPMENT OF ROLL REDUCTION DEVICES

Viewgraph 17 presents the simplified lateral ship motion equations used to develop antiroll tanks. That is, the entire remainder of my talk will now concentrate on what is and can be done to stabilize our ships in the roll mode. Three different devices will be discussed. These are roll tanks, fins, and ship rudders.

SHIP STABILIZATION WITH ANTIROLL TANKS

Antiroll tanks have been installed on thousands of commercial ships and until fairly recently on many of our combatant naval ships. It is perhaps instructive to note that the reports from our "pilots," that is the ship CO's, have indicated that tanks don't work and in fact destabilize. DTNSRDC's technical director and our department however do not concur with the reported "uselessness of antiroll tanks". For this reason, therefore, we have had underway a program to establish the validity of the tank performance reports or alternately to establish in some detail the performance attributes of such tanks. The results will demonstrate these attributes.

I should also point out that our interest in tanks is associated with the fact that they tend to work best when you, the aircraft operators, need roll stabilization the most - namely at relatively slow ship speeds. The winds associated with the onset of a storm tend to force the ship to slow down both to minimize the vertical ship responses that produce aircraft launch/takeoff difficulties and to maintain the relative wind to acceptably low values of 45 knots or less. Under these conditions an unstabilized ship tends to increase roll, and fin stabilizers or rudder roll stabilizers become less and less effective because both require ship speed to generate the lift and thus produce their stabilizing moment. Antiroll tanks on the other hand become more effective in stabilizing primarily because their stabilizing moment which is speed independent becomes a larger and larger fraction of the total ship roll damping moment as speed decreases.

At any rate, the model basin (DTNSRDC) has developed a hybrid facility where a physical model of a ship tank is driven by a roll and lateral tank

motion signal generated by feeding roll, sway, and yaw wave exciting force/moment time histories into the simplified math model of the ship illustrated in the viewgraph. The tank moment in turn is added to the wave exciting moment to produce the stabilized roll of the ship. Viewgraph 17 presents a block diagram of this tank test/evaluation facility.

Viewgraph 19 presents some of the experimental validation for this facility. Time histories of a ship model rolling in longcrested, irregular beam waves at zero speed in the maneuvering basin at DTNSRDC are shown. The model test results were obtained both with the tank unstabilized and stabilized. The waves which produced these results as well as the tank itself were then placed into our tank facility and used to drive our hybrid ship math model/physical tank model system. The results are superimposed on this graph. You can't see significant differences between the experimental and the hybrid facility results because the differences were rather small for this beam sea example. (Model tests are solid lines; facility results are the dotted lines.)

We had reason to believe however that the results would be somewhat worse as seas came from less favorable headings and thus we built two additional ship math models to further validate the operation of our facility. Some of the results of this work are given on the 20th viewgraph. It is apparent that there are significant differences or improvements between the unstabilized (solid lines) and the stabilized results.

The vertical axis presents results in terms of the RMS values, and the horizontal axis represents the modal period of the irregular seas for which these tests were made. Again I point out that our naval architectural convention for headings is different from yours, i.e. 180^{o} represents waves coming from directly ahead, 90^{o} represents waves moving towards the port beam, and 0^{o} has waves moving towards the stern. Longcrested wave results are shown in the top graphs and shortcrested results are shown in the bottom graphs.

All three sets of ship math models give similar results as far as trends are concerned. Tanks clearly produce worthwhile, significant roll stabilization throughout most of the range of possible ship operating conditions. The

destabilization noted by the ship operators does occur, though it is not important because it occurs when roll is very small and does not impact operation. Thus in conclusion our basic question about the usefulness of roll tanks is answered affirmatively. Tanks produce significant roll stabilization at the lower ship speeds where such stabilization is most important for VSTOL or aircraft operations.

The fleet reports regarding destabilization are somewhat suspect because there is no clear way for an operator to assess the roll stabilization performance of a tank if, as is the case for our USN combatants, it requires several hours to alter significantly the stabilization status (fluid level) of the tanks i.e., there is no rapid on/off switch for the tanks.

SHIP STABILIZATION WITH ANTIROLL FINS

With viewgraph 21 we briefly turn to the subject of antiroll or roll stabilizing fins. The time domain fin system model of the viewgraph illustrates a number of similarities with some of the control or stabilization diagrams for your VSTOL aircraft shown yesterday. Thus both of our technical communities appear to be using some essentially similar techniques for "control or stabilization." At any rate I would like to report to you a change in USN ship construction policy that will significantly impact on your VSTOL flying qualities and handling design tasks as far as control power margins are concerned. The USN except for the FF1052 ship class generally did not outfit combatant ships (i.e. ships from which your VSTOL operate) with roll stabilizing fins. All major foreign (and most minor ones also) have for years adopted the policy that roll fins are installed as a matter of course during the construction of new naval combatants. The USN is just now in the process of adopting a similar policy. Thus the ship motion environment in which your VSTOL aircraft must operate will be significantly improved as or when ships with fin stabilizers become operational.

SHIP STABILIZATION WITH RUDDERS

Next, I would like to turn to the subject of the roll stabilization of the current navy combatants which do not have either anti-roll tanks or roll fins. For this rather large group of ships it is my opinion that the new fin policy is not going to result in a massive roll fin back-fitting program. Thus for this group of ships an alternate, cheaper, though less roll reduction performance system is under current development. This alternative is to use

the ship's rudder as a stabilizer. We have been engaged for the past two years in a joint USN/USCG program to develop such a system.

The remainder of the presentation is devoted to a description of this program, its history, future and of course the currently available full scale trial results.

A major ship/helicopter interface program that followed our work with NATC on the BOWEN with the SH-2D was initiated by the USCG in the fall of 1974. This program was to develop flight envelopes and percentage of expected usage for the USCG HAMILTON Ship Class with their H-3 helos.

About four weeks of at-sea interface testing with this ship/helicopter team was performed. At the completion of the first of these trials off the northeast coast i.e., Boston/Newfoundland and the gulf of Maine, we learned again the difficulties of trying to get the sea states when the aircraft was operational. A major lesson learned was that the use of the USCG landing grid with this H-3 helicopter would result in crunched main landing gears. It is to be noted that the landing grid is used by the USCG with their other seagoing helicopter, the rather light H-52, to prevent lateral sliding on the deck.

The removal of this landing grid for the second at sea test period caused us some concern about the possible safety hazards of landing the relatively large H-3 helo with its rather high CG on the rather small deck of the 3000 ton HAMILTON. We were particularly concerned with ship roll related hazards, namely dynamic roll over, landing gear failures due to excessive lateral loads, and finally lateral sliding on the deck. Viewgraph 22 illustrates graphically the forces and situation that worried us.

Viewgraph 23 further illustrates the results from a rather simple simulation made prior to the second at-sea interface trials. The graph illustrates for various combinations of thrust-to-weight ratio on a relative lateral velocity vs roll motion graph, the regions where dynamic roll over might occur. Thus for example if the helicopter was to contact the flight deck during its landing while the ship had an instantaneous roll angle of 15 degree with a

relative lateral velocity between the landing gear and the deck of somewhat more than 5.5 ft per second the aircraft would roll over-provided that the thrust-to-weight ratio for these initial conditions was equal to 0.2. The situation, of course, would have been worse if the helo had a much greater thrust to weight ratio at this instant during landing.

These pre-trial results suggested to us the usefulness of roll stabilization during these trials. Therefore a joint USN/USCG program was initiated to use the HAMILTON'S rudder as a roll stabilizer.

The successful use of a ship's rudder for roll stabilization depends on three basic factors, all of which have to be met successfully. First, the rudder must be capable of producing large roll excitations; secondly, the rudder controller must be capable of efficiently using this rudder capacity to reduce roll; and third, the potential penalties associated with the use of the rudder as a stabilizer must be negligibly small.

The first factor essentially defines the physical status of the ship and the steering system. That is, this factor defines:

a. Is the ship heavily or lightly damped in roll?

b. Does it have a small or large GM i.e. is ship roll tender or stiff?

c. Is the rudder large enough, located far enough from the roll center, and fast enough to move at the predominant roll frequencies?

The second factor basically deals with capacity of the rudder machinery/servo system and the electronic controller to efficiently use the rudder induced roll moments to counteract the sea induced roll moments. That is,

a. Can the rudder respond fast enough with enough rudder angle to a rudder command signal developed by the controller to cancel rather than reinforce the random roll of the ship?

b. Can the controller produce from the ship's roll signal a signal that will have the rudder position (angle) lead roll motion by 90^{o} i.e. feed ahead or phase lag compensation to cancel roll?

The third factor deals with the magnitudes of the potential penalties as well as cost incurred by the use of the rudder as a stabilizer. That is,

a. Are the rudder system loads (mechanical, electrical, and hydraulic) and the resultant system wear sufficiently low so as not to affect the reliability and maintenance requirements of the system?

b. Are the steering/coursekeeping capabilities either unaffected or improved?

c. Will the installation cost of the system be very modest (15-20 K$) per ship?

A series of trials thus commencing with the second at sea deployment of the HAMILTON with the H-3 were thus initiated. Fortunately the seas during this first deployment of the rudder as a roll stabilizer (see viewgraph 24), did not result in seas that produced roll and thus potential hazards for the H-3 landings/takeoffs aboard the HAMILTON. As a result of the mild seas we had to conduct forced roll tests with the rudder. These results indicated that modifications to the steering ram pressure controller would be mandatory if the rudder was to function acceptably i.e., fast enough, accurately enough, and with sufficient rudder angle at roll frequencies.

A second sea trial conducted in the Pacific from Hawaii to Kodiak (see Viewgraph 25), with a sister ship of the HAMILTON, the MELLON, indicated the need for further mechanical and electronic controller refinements in the modified steering ram controller system.

In passing it may be noted that the initial photographs illustrating ship operating limitations of pitch, deck wetness and roll were taken during this trial i.e. see the 42N, 162W course. In fact the rudder roll stabilization testing conducted during this building storm indicated clearly the desirability of an actively varying control law that adjusts to the roll motions of the ship. This rather important lesson was thus carried out as part of the next trial effort.

The refinements to the DTNSRDC steering ram controller were made and re-installed aboard the MELLON for its June-July 76 trip from Seattle to Hawaii. The resultant measured roll reductions were sufficiently large and desirable to justify two prototypes being prepared for permanent installation aboard the HAMILTON and the MELLON so that an operator evaluation of these systems can be performed.

The rudder roll and steering system control block diagram is given on the 26th viewgraph. Since in many respects it is similar to others shown here, no

further comments are made - except to point out that (roll) velocity control is being used to command the rudder stabilization activity.

Finally, we come to the bottom line, how did this rudder roll stabilizer system perform? A sample of three successive one-half hour runs of the ship in moderate beam seas is shown. The first run was unstabilized and is denoted by a U, the second was stabilized and is denoted by an S, and the third run was again unstabilized and is also denoted by U.

The next three viewgraphs present time histories of the rudder action, and the associated yaw (steering) and roll responses. The activity of the helmsman is quite evident in the unstabilized roll rudder traces (viewgraph 27). The increase in rudder activity incurred when the rudder is used as a stabilizer is equally evident. Discussions with the manufacturer of the steering gear suggested that rudder activity at these moderate angles would not result in excessive wear loads on the bearings or other parts of the steering system.

The ship's steering or yaw response to the roll stabilization rudder action is seen to be negligible (viewgraph 28). In fact, it should be noted that the helmsman indicated that it was definitely easier to steer the ship when the rudder was engaged as a roll stabilizer.

The roll stabilization achieved by the rudder is evident in viewgraph 29. The use of the velocity control law roll stabilization is clearly reflected in the results. The largest roll amplitudes which are so evident in the beat pattern of the unstabilized ship are very evidently strongly reduced. Thus the ship roll in the stabilized mode appeared to be much more comfortable than indicated by the reduction in the significant roll amplitudes (7.12° double amplitudes vice 10.7 to 11.6° double amplitudes).

As a result of the above trials I feel confident in predicting that even our current ships without roll stabilization are likely to have at least rudder roll stabilization by the time the VSTOL aircraft are to operate off or with these ships.

Our current plans regarding rudder roll stabilization are outlined in the following two viewgraphs.

SUMMARY OF CONCLUSIONS

1) VSTOL ships are likely to be affected primarily by swell which is independent of the local wind rather than the wind related shortcrested local seas.
2) The common assumption that wind direction and wave direction coincide is generally true only in a storm. Thus true wind and waves that produce ship motions do not align!
3) Predicted statistical ship motions given in RMS/T_{oe} tables will define operational regions where large ship responses occur and will thus define the expected ship motion environment for the VSTOL ships.
4) The smallest ship (3000 ton destroyer type vice 7300 ton DD963 or 17000 ton LPH) does not necessarily have the worst responses in all motion modes that interfere with VSTOL operations.
5) Angular pitch motion by itself is a misleading indicator of ship motions when several ships are being compared.
6) LPH/AV8A Sea trials in 1972-73 indicated that the most frequent components of ship motion that produced difficulties in the launch/recovery operations were the vertical plane responses of pitch and heave.
7) The poor predictability of bow attitude was the most frequent cause of launch delays or cancellations. Significant pitch motions of $\pm$ 0.5° were sufficient to limit the launching operations.
8) AV8A launch/recovery operations were generally delayed when significant pitch ranged between $\pm$ 1.7° to $\pm$ 2.1°.
9) AV8A launch/recovery operations were generally cancelled when significant pitch ranged between $\pm$ 2.1° to 2.8°.
10) No AV8A launch/recovery operations occurred when significant pitch was greater than $\pm$ 2.8°!
11) The reduction of roll will have a beneficial effect on the performance of various tasks such as STOL or VTOL from ships by reducing the probability of sliding, etc.

12) To improve future naval VSTOL operations we must develop a lull predictor that gives us at least 8-10 second forecast into the future for pitch and pitch related responses and 20 second forecast in the future for roll.

13) Experimental results indicate that anti-roll tanks will produce significant roll stabilization at the lower ship speeds where such stabilization is most important for VSTOL or aircraft operations.

14) It is concluded that the ship motion environment in which future VSTOL aircraft must operate will be significantly improved as or when ships with fin stabilizers become operational.

15) Even our current ships without roll stabilization are likely to have at least rudder roll stabilization by the time the VSTOL aircraft are to operate off or with these ships.

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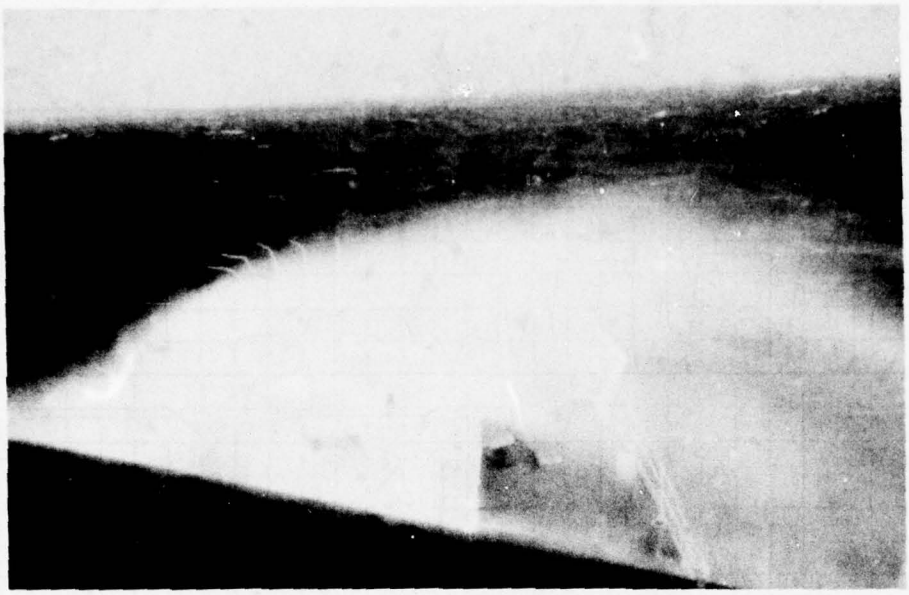


FIG. 1 USCG WHEC Mellon encountering storm sea

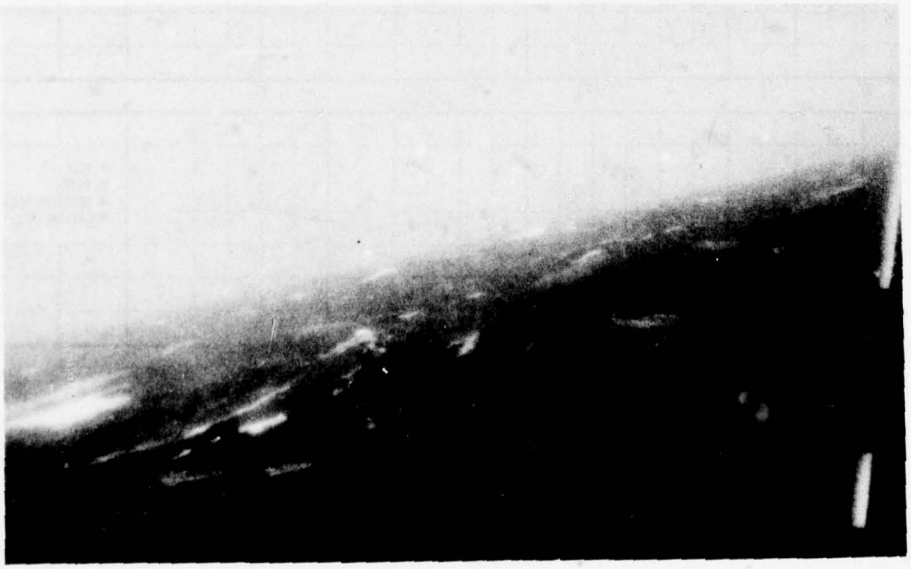
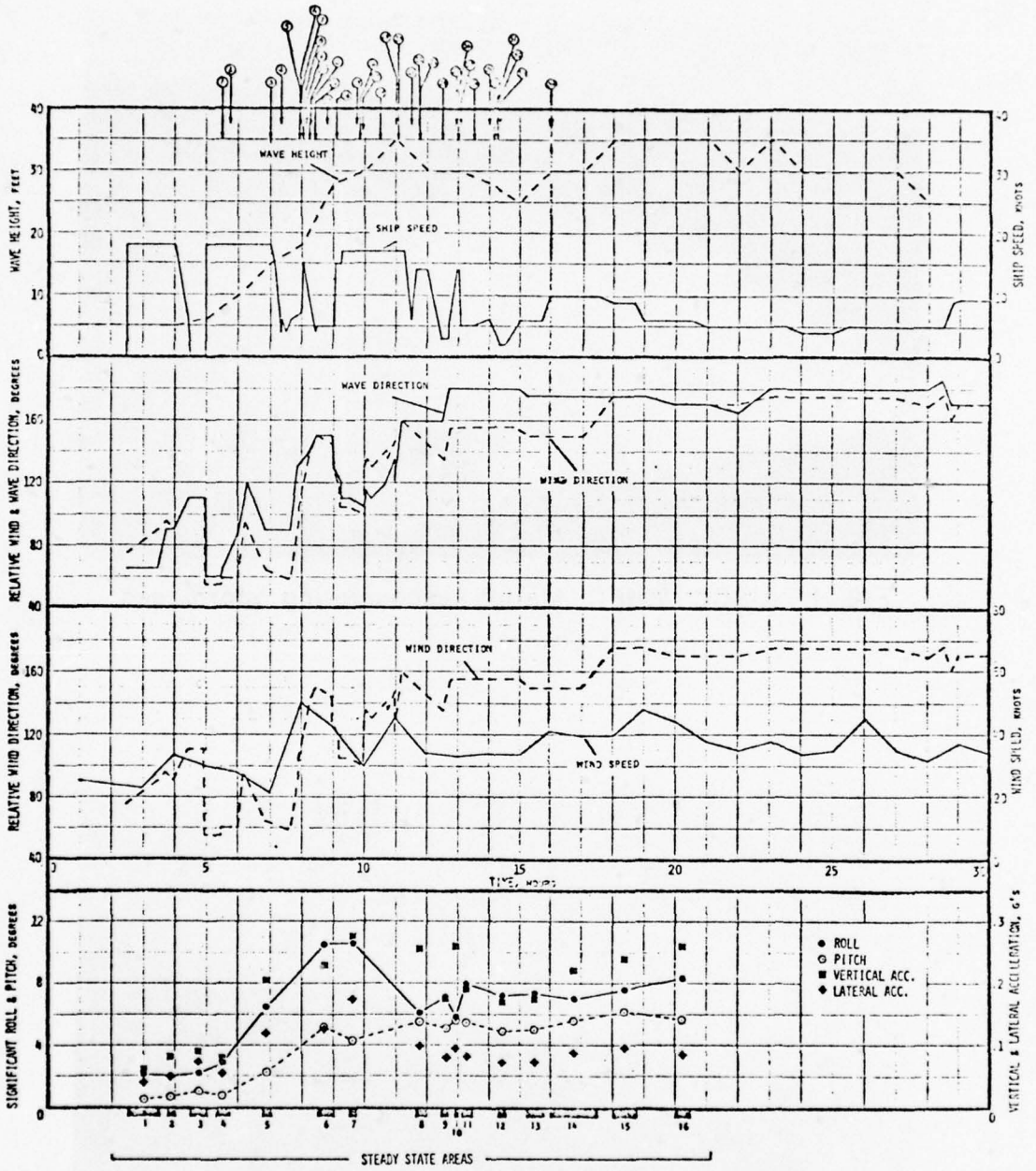


FIG. 2 USCG WHEC Mellon with Limit Roll Angle

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SHIP: USCG WHEC-717 *Mellon*, 378 Feet LOA, 3000 Tons
LOCATION: North Pacific - 42N 162W, May 1976



Viewgraph 3: Hindcast Ship Motions in a May 1976 Storm

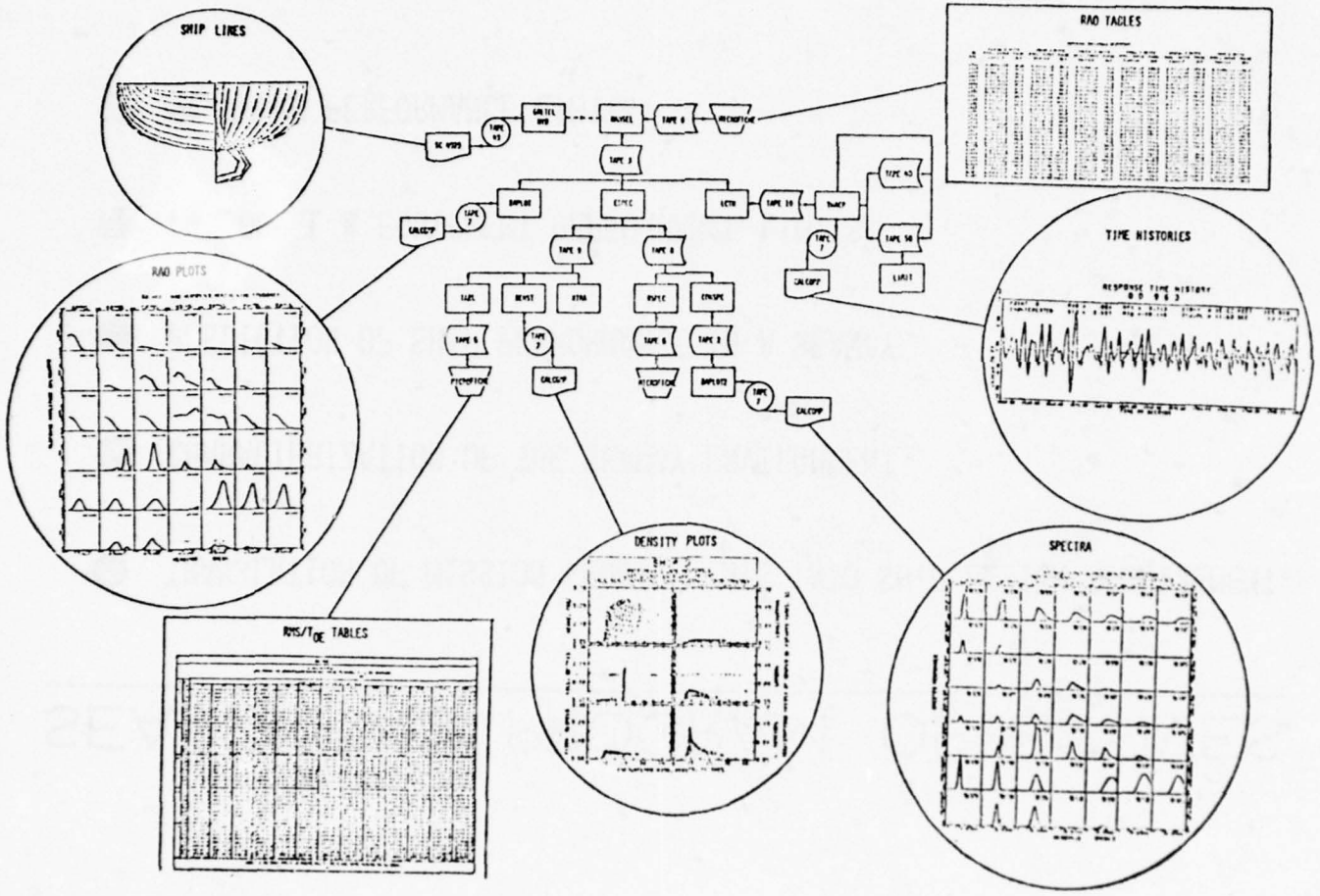
SEAKEEPING PROGRAM OBJECTIVES

- TRANSLATION OF MISSION REQUIREMENTS INTO SHIP DESIGN REQUIREMENT
- CHARACTERIZATION OF THE SEAWAY ENVIRONMENT
- PREDICTION OF SHIP PERFORMANCE IN A SEAWAY
- PERSONNEL & EQUIPMENT PERFORMANCE LIMITS
- PLATFORM PERFORMANCE LIMITS

Viewgraph 4: Objectives of a Current 1977 Seakeeping Research Program

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Viewgraph 5: Current DTNSRDC Ship Motion Prediction Computer Program



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DD 963

LONGCRESTED

RMS ROLL IN DEGREES/ENCOUNTERED MODAL PERIOD, T_{OE} IN SECONDS

SHIP HEADING ANGLE IN DEGREES

V	T0	0	15	30	45	60	75	90	105	120	135	150	165	180
5	7	.000/11.2	.088/ 9.8	.133/11.2	.166/10.8	.200/ 9.8	.217/ 8.7	.104/ 8.7	.164/ 7.1	.129/ 7.7	.071/ 7.9	.044/ 8.1	.021/ 6.3	.000/*****
	9	.000/11.2	.149/11.6	.264/11.6	.372/11.2	.431/10.8	.396/10.8	.237/10.5	.282/10.8	.210/10.5	.200/10.1	.131/10.1	.070/11.2	.000/*****
	11	.000/11.2	.161/11.6	.305/11.6	.440/11.2	.507/11.2	.459/10.8	.320/11.2	.369/10.8	.375/10.8	.309/11.2	.225/11.2	.133/11.2	.000/*****
	13	.000/11.2	.147/11.6	.284/11.6	.412/11.2	.474/11.2	.432/11.2	.321/11.2	.373/11.2	.341/11.6	.339/11.6	.260/11.2	.154/11.2	.000/*****
	15	.000/11.2	.126/11.6	.246/11.6	.356/11.2	.409/11.2	.376/11.2	.288/11.2	.336/11.2	.359/11.6	.321/11.6	.251/11.2	.154/11.2	.000/*****
	17	.000/11.2	.106/11.6	.208/11.6	.300/11.6	.345/11.2	.318/11.6	.248/11.6	.291/11.2	.314/11.6	.284/11.6	.225/11.2	.139/11.2	.000/*****
	19	.000/11.2	.089/11.6	.175/11.6	.253/11.6	.290/11.2	.268/11.6	.212/11.6	.248/11.2	.270/11.6	.246/11.6	.196/11.2	.120/11.2	.000/*****
	21	.000/11.2	.076/11.6	.148/11.6	.214/11.6	.245/11.2	.227/11.6	.181/11.6	.212/11.2	.231/11.6	.212/11.6	.169/11.2	.104/11.2	.000/*****
10	7	.000/13.4	.110/12.8	.375/11.6	.333/10.1	.284/10.5	.253/ 9.0	.104/ 8.5	.136/ 7.0	.098/ 7.7	.059/ 7.7	.038/ 8.1	.014/ 8.1	.000/*****
	9	.000/13.4	.111/12.8	.342/11.6	.470/11.2	.470/11.2	.394/10.8	.206/10.5	.213/10.8	.148/ 9.8	.131/10.1	.084/10.1	.040/10.1	.000/*****
	11	.000/13.4	.100/12.8	.286/11.5	.394/12.6	.426/11.2	.371/11.2	.271/11.2	.276/11.2	.264/11.6	.211/11.6	.150/11.2	.088/12.8	.000/*****
	13	.000/13.4	.088/12.8	.237/11.5	.330/12.6	.439/11.6	.348/11.2	.272/11.2	.267/12.1	.291/11.6	.263/11.6	.194/12.6	.122/12.8	.000/*****
	15	.000/13.4	.076/12.8	.196/11.6	.274/12.6	.330/11.6	.335/11.2	.246/11.6	.265/12.1	.279/11.6	.251/12.1	.201/12.6	.129/12.8	.000/*****
	17	.000/13.4	.065/12.8	.163/11.6	.247/12.8	.307/11.6	.280/11.6	.213/11.6	.234/12.1	.251/12.1	.232/12.8	.188/12.6	.122/12.8	.000/*****
	19	.000/13.4	.056/12.8	.136/11.6	.207/12.8	.258/11.6	.236/11.6	.183/11.6	.202/12.1	.220/12.1	.206/12.8	.166/12.6	.109/12.8	.000/*****
	21	.000/13.4	.048/12.8	.115/11.6	.175/12.8	.218/12.1	.199/11.6	.157/11.6	.174/12.1	.191/12.1	.180/12.8	.147/12.6	.095/12.8	.000/*****
15	7	.000/22.4	.034/20.9	.089/18.0	.259/19.3	.370/11.6	.296/ 9.2	.098/ 8.5	.114/ 7.5	.076/ 7.7	.041/ 7.9	.021/ 8.1	.010/ 8.3	.000/*****
	9	.000/20.3	.043/19.6	.110/17.5	.206/14.3	.463/12.1	.392/10.8	.177/10.5	.167/10.1	.138/ 9.2	.093/ 9.2	.057/ 9.2	.024/ 9.2	.000/*****
	11	.000/20.3	.051/19.6	.122/17.5	.264/15.0	.449/12.1	.390/11.2	.226/11.2	.212/12.1	.188/11.6	.147/11.6	.104/12.6	.058/12.8	.000/*****
	13	.000/20.3	.052/19.6	.120/17.5	.238/15.0	.384/12.6	.351/11.6	.228/11.6	.225/12.1	.214/12.1	.181/12.8	.139/12.6	.084/12.8	.000/*****
	15	.000/20.3	.049/19.6	.110/18.0	.208/15.3	.324/12.6	.298/11.6	.207/11.6	.214/12.1	.212/13.1	.188/12.8	.156/12.6	.093/14.3	.000/*****
	17	.000/20.3	.044/19.6	.097/18.0	.176/15.7	.270/12.6	.250/11.6	.182/11.6	.192/12.1	.196/13.1	.178/12.8	.165/14.3	.092/14.3	.000/*****
	19	.000/20.3	.039/19.6	.085/18.	.149/15.7	.226/12.6	.210/11.6	.157/11.6	.168/12.1	.174/13.1	.162/13.1	.133/14.3	.084/14.3	.000/*****
	21	.000/20.3	.035/19.6	.074/18.	.126/15.7	.190/12.8	.178/11.6	.136/11.6	.147/12.1	.153/13.1	.144/13.1	.119/14.3	.076/14.3	.000/*****
20	7	.000/69.8	.053/ 7.0	.060/24.2	.126/19.0	.399/13.4	.357/ 9.8	.099/ 8.5	.101/ 7.5	.064/ 7.7	.032/ 7.9	.016/ 8.1	.007/ 8.3	.000/*****
	9	.000/27.3	.045/26.2	.060/23.3	.175/19.0	.455/13.4	.446/10.8	.173/10.5	.146/10.1	.116/ 9.2	.075/ 9.2	.045/ 9.2	.021/ 9.2	.000/*****
	11	.000/27.3	.047/26.2	.097/23.3	.194/19.0	.423/13.7	.426/11.2	.219/11.2	.184/12.1	.160/11.6	.117/11.6	.080/11.6	.043/12.8	.000/*****
	13	.000/27.3	.047/26.2	.100/23.3	.195/19.0	.361/13.7	.366/11.6	.221/11.6	.205/12.1	.187/13.1	.148/12.8	.109/14.3	.064/14.3	.000/*****
	15	.000/27.3	.044/26.2	.093/23.3	.169/19.0	.301/13.7	.309/11.6	.201/11.6	.199/12.1	.191/13.1	.159/14.6	.123/14.3	.076/14.3	.000/*****
	17	.000/27.3	.040/26.2	.084/23.3	.144/19.0	.251/13.7	.258/12.1	.177/11.6	.181/13.4	.180/13.4	.155/14.6	.126/14.3	.074/14.3	.000/*****
	19	.000/27.3	.035/26.2	.074/23.3	.123/19.0	.210/13.7	.214/12.1	.153/11.6	.160/13.4	.163/13.4	.146/14.6	.117/14.3	.075/14.3	.000/*****
	21	.000/27.3	.032/26.2	.065/23.3	.108/19.0	.177/13.7	.181/12.1	.132/11.6	.140/13.4	.144/13.4	.130/14.6	.107/14.3	.069/14.3	.000/*****
25	7	.000/ 7.9	.045/ 7.5	.095/ 7.0	.109/26.2	.277/15.5	.459/10.1	.098/ 8.4	.089/ 7.5	.054/ 7.7	.026/ 7.9	.013/ 8.1	.006/ 8.1	.000/*****
	9	.000/48.3	.044/44.9	.094/33.1	.153/24.2	.356/15.5	.507/11.2	.168/10.5	.127/ 9.8	.097/ 9.5	.062/ 9.5	.037/ 9.2	.017/ 9.2	.000/*****
	11	.000/37.0	.049/34.9	.102/29.9	.173/24.2	.346/15.5	.459/11.6	.211/11.2	.163/12.	.133/11.6	.097/11.6	.066/11.2	.034/11.2	.000/*****
	13	.000/34.9	.048/33.1	.101/29.9	.167/24.2	.304/15.5	.387/11.6	.212/11.6	.182/12.1	.156/13.1	.124/13.1	.092/14.3	.052/14.3	.000/*****
	15	.000/34.9	.046/33.1	.094/29.9	.151/24.2	.259/15.5	.319/12.1	.194/11.6	.190/13.4	.164/13.4	.137/14.6	.110/14.3	.067/14.3	.000/*****
	17	.000/34.9	.042/33.1	.086/29.9	.133/24.2	.217/15.5	.264/12.1	.170/11.6	.166/13.4	.158/15.0	.134/14.6	.115/14.6	.073/14.3	.000/*****
	19	.000/34.9	.037/33.1	.075/29.9	.116/24.2	.182/15.5	.220/12.1	.147/11.6	.144/13.7	.145/15.0	.131/14.6	.112/14.6	.072/16.1	.000/*****
	21	.000/34.9	.033/33.1	.066/29.9	.101/24.2	.156/15.5	.165/12.1	.128/12.6	.131/13.7	.131/15.0	.120/14.6	.104/14.6	.068/16.1	.000/*****

NOTE: V IS SHIP SPEED IN KNOTS AND T_0 IS MODAL WAVE PERIOD IN SECONDS.

Viewgraph 6: Roll Motion RMS/T_{OE} Table for the DD 963 in Longcrested Seas with 1-Foot Significant Wave Height

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DD 963

SHORTCRESTED

RMS ROLL IN DEGREES/ENCOUNTERED MODAL PERIOD, T_{OE}, IN SECONDS

SHIP HEADING ANGLE IN DEGREES

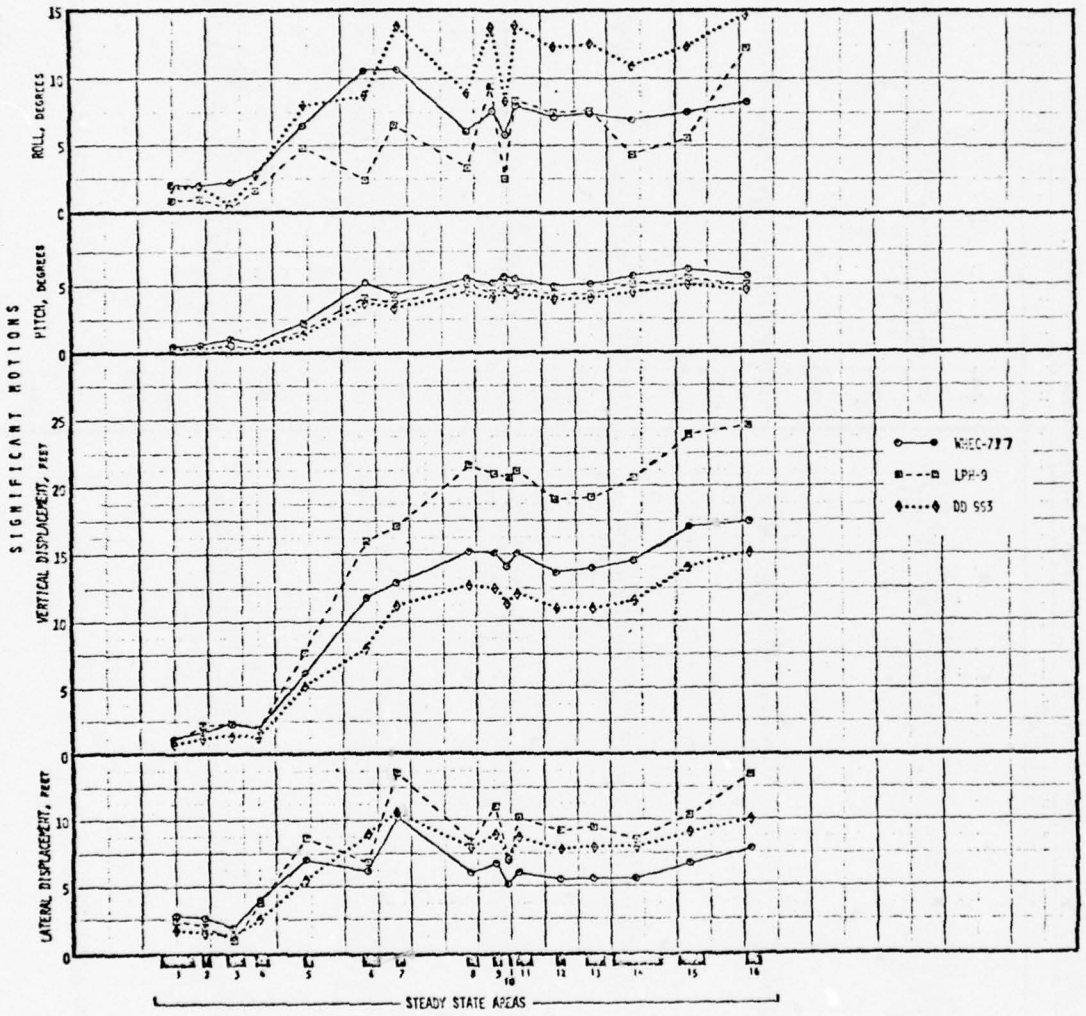
V	T_0	0	15	30	45	60	75	90	105	120	135	150	165	180
5	7	.126/10.8	.130/10.8	.141/10.8	.152/10.5	.160/10.5	.162/ 9.6	.156/ 9.5	.143/ 9.0	.125/ 8.3	.103/ 7.9	.083/ 7.9	.066/ 7.7	.060/ 7.9
	9	.257/11.2	.266/11.2	.286/11.2	.308/11.2	.322/11.2	.324/11.2	.310/10.8	.284/10.8	.249/10.5	.211/10.5	.176/10.5	.152/10.5	.142/10.5
	11	.300/11.6	.310/11.6	.337/11.6	.366/11.2	.388/11.2	.396/11.2	.389/11.2	.366/11.2	.332/11.2	.294/11.2	.257/11.2	.231/11.2	.221/11.2
	13	.279/11.6	.290/11.6	.316/11.6	.346/11.6	.370/11.6	.383/11.2	.381/11.2	.366/11.2	.340/11.2	.309/11.2	.276/11.2	.253/11.2	.244/11.2
	15	.241/11.6	.251/11.6	.274/11.6	.301/11.6	.324/11.6	.337/11.6	.334/11.6	.329/11.2	.309/11.2	.284/11.2	.258/11.2	.239/11.2	.231/11.2
	17	.204/11.6	.212/11.6	.231/11.6	.255/11.6	.275/11.6	.286/11.6	.284/11.6	.284/11.6	.269/11.6	.248/11.6	.227/11.2	.211/11.2	.205/11.2
	19	.171/11.6	.178/11.6	.195/11.6	.215/11.6	.233/11.6	.244/11.6	.248/11.6	.248/11.6	.230/11.6	.213/11.6	.196/11.6	.183/11.2	.178/11.2
	21	.145/11.6	.151/11.6	.165/11.6	.182/11.6	.197/11.6	.207/11.6	.211/11.6	.207/11.6	.197/11.6	.183/11.6	.168/11.6	.157/11.2	.153/11.2
10	7	.256/11.6	.257/11.6	.258/11.6	.257/11.6	.250/11.6	.233/11.6	.203/11.6	.166/10.1	.128/10.1	.095/ 8.1	.068/ 7.9	.051/ 7.7	.045/ 7.7
	9	.288/11.6	.295/11.6	.313/11.6	.330/11.6	.337/11.6	.328/11.6	.302/11.6	.262/11.6	.214/10.8	.167/10.8	.128/10.5	.103/10.1	.095/10.1
	11	.273/11.6	.283/11.6	.309/11.6	.335/11.6	.352/11.6	.352/11.6	.336/11.6	.305/11.6	.265/11.2	.222/11.2	.185/11.2	.160/11.6	.152/11.6
	13	.237/11.6	.243/11.6	.273/11.6	.300/11.6	.320/11.6	.327/11.6	.321/11.6	.301/11.6	.272/11.6	.240/11.6	.210/11.6	.190/12.1	.183/12.1
	15	.199/11.6	.209/11.6	.231/11.6	.257/11.6	.276/11.6	.286/11.6	.285/11.6	.273/11.6	.253/12.1	.229/12.1	.206/12.6	.190/12.6	.184/12.6
	17	.167/11.6	.175/11.6	.194/11.6	.216/12.1	.234/12.1	.244/12.1	.246/12.1	.238/12.1	.224/12.1	.205/12.1	.187/12.6	.175/12.6	.170/12.6
	19	.140/12.1	.147/12.1	.163/12.1	.182/12.1	.198/12.1	.208/12.1	.210/12.1	.205/12.1	.194/12.1	.179/12.6	.165/12.6	.155/12.6	.151/12.6
	21	.118/12.1	.124/12.1	.136/12.1	.154/12.1	.168/12.1	.177/12.1	.180/12.1	.176/12.1	.168/12.1	.156/12.6	.144/12.6	.135/12.6	.132/12.6
15	7	.158/14.3	.164/14.3	.189/14.3	.209/14.3	.219/14.3	.215/14.3	.198/10.1	.170/10.1	.133/10.1	.093/10.1	.059/ 8.3	.040/ 7.7	.036/ 7.7
	9	.193/14.3	.207/14.3	.238/14.3	.267/12.1	.283/12.1	.283/11.6	.266/11.6	.233/11.6	.190/11.6	.141/11.2	.100/10.5	.076/ 9.5	.069/ 9.2
	11	.191/14.3	.205/14.3	.237/12.1	.268/12.1	.288/12.1	.292/12.1	.280/12.1	.253/12.1	.216/11.6	.174/11.6	.137/11.6	.114/11.6	.106/11.6
	13	.171/15.0	.183/14.3	.212/12.1	.241/12.1	.261/12.1	.269/12.1	.263/12.1	.245/12.1	.218/12.1	.186/12.1	.157/12.6	.138/12.6	.132/12.6
	15	.147/17.5	.157/15.0	.182/12.6	.207/12.1	.226/12.1	.235/12.1	.234/12.1	.223/12.1	.203/12.6	.180/12.6	.158/12.6	.143/12.8	.138/12.8
	17	.125/17.5	.133/17.5	.154/15.0	.176/12.6	.193/12.6	.202/12.6	.204/12.6	.196/12.6	.182/12.6	.164/12.8	.147/13.1	.135/13.1	.131/13.1
	19	.106/17.5	.113/17.5	.130/15.0	.149/12.6	.164/12.6	.173/12.6	.175/12.6	.171/12.6	.160/12.8	.146/13.1	.132/13.1	.123/13.4	.119/13.4
	21	.090/17.5	.097/17.5	.111/15.0	.127/12.6	.140/12.6	.148/12.6	.151/12.6	.148/12.8	.139/12.9	.128/13.1	.117/13.4	.109/14.0	.106/14.3
20	7	.143/13.4	.157/13.4	.187/13.4	.214/13.4	.228/13.4	.227/13.4	.212/13.4	.184/13.4	.145/13.4	.100/13.4	.059/ 9.5	.034/ 7.7	.029/ 7.7
	9	.170/13.4	.188/13.4	.226/13.4	.259/13.4	.278/13.4	.280/13.4	.265/13.4	.234/13.4	.190/13.4	.139/10.5	.092/10.5	.064/ 9.5	.056/ 9.2
	11	.168/13.7	.185/13.7	.221/13.7	.254/13.7	.275/13.7	.280/13.7	.269/13.7	.243/13.7	.205/13.4	.160/11.6	.119/11.6	.094/11.6	.084/11.6
	13	.151/19.0	.165/19.0	.196/13.7	.226/13.7	.247/13.7	.255/13.7	.249/13.7	.231/13.7	.202/13.4	.164/12.1	.136/12.6	.115/12.8	.104/13.1
	15	.131/19.0	.142/19.0	.168/13.7	.194/13.7	.213/13.7	.223/13.7	.221/13.7	.209/13.7	.184/13.4	.163/13.4	.139/13.4	.123/14.3	.117/14.3
	17	.112/19.0	.121/19.0	.143/19.0	.165/13.7	.182/13.7	.192/13.7	.193/13.7	.185/13.7	.170/13.7	.151/13.7	.132/14.3	.119/14.3	.115/14.3
	19	.095/19.0	.103/19.0	.121/19.0	.140/13.7	.155/13.7	.164/13.7	.166/13.7	.162/13.7	.150/13.7	.135/13.7	.121/14.3	.110/14.3	.107/14.3
	21	.082/23.3	.089/19.0	.103/19.0	.120/13.7	.133/13.7	.141/13.7	.144/13.7	.140/13.7	.132/13.7	.120/14.3	.108/14.3	.100/14.3	.097/14.3
25	7	.125/16.5	.143/16.5	.177/16.5	.205/16.5	.222/16.5	.225/16.5	.214/16.5	.189/16.5	.152/16.5	.108/10.1	.062/10.1	.030/ 7.7	.024/ 7.7
	9	.152/16.5	.172/16.5	.212/16.5	.246/16.5	.267/16.5	.271/16.5	.259/16.5	.230/16.5	.188/16.5	.137/16.5	.087/10.8	.054/ 9.5	.047/ 9.2
	11	.152/16.5	.169/16.5	.206/16.5	.239/16.5	.260/16.5	.266/16.5	.256/16.5	.231/16.5	.194/16.5	.150/11.6	.107/11.6	.079/11.6	.071/11.6
	13	.139/16.5	.152/16.5	.183/16.5	.213/16.5	.233/16.5	.240/16.5	.235/16.5	.214/16.5	.178/16.5	.153/12.1	.120/12.6	.098/13.1	.091/13.4
	15	.120/16.5	.132/16.5	.159/16.5	.185/16.5	.201/16.5	.210/16.5	.209/16.5	.196/16.5	.175/16.5	.149/13.1	.124/13.7	.108/14.3	.102/14.6
	17	.104/16.5	.113/16.5	.134/16.5	.156/16.5	.172/16.5	.181/16.5	.180/16.5	.170/16.5	.159/16.5	.139/13.7	.121/14.3	.108/14.6	.104/14.6
	19	.089/16.5	.097/16.5	.114/16.5	.133/16.5	.147/16.5	.156/16.5	.157/16.5	.152/16.5	.141/16.5	.127/14.3	.112/14.6	.103/14.6	.099/14.6
	21	.077/16.5	.083/16.5	.098/16.5	.114/16.5	.126/16.5	.134/16.5	.137/16.5	.133/16.5	.125/16.5	.113/14.6	.102/14.6	.094/14.6	.091/14.6

NOTE: V IS SHIP SPEED IN KNOTS AND T_0 IS MODAL WAVE PERIOD IN SECONDS.

Viewgraph 7: Roll Motion RMS/T_{OE} Table for the DD 963 in Shortcrested Seas with 1-Foot Significant Wave Height

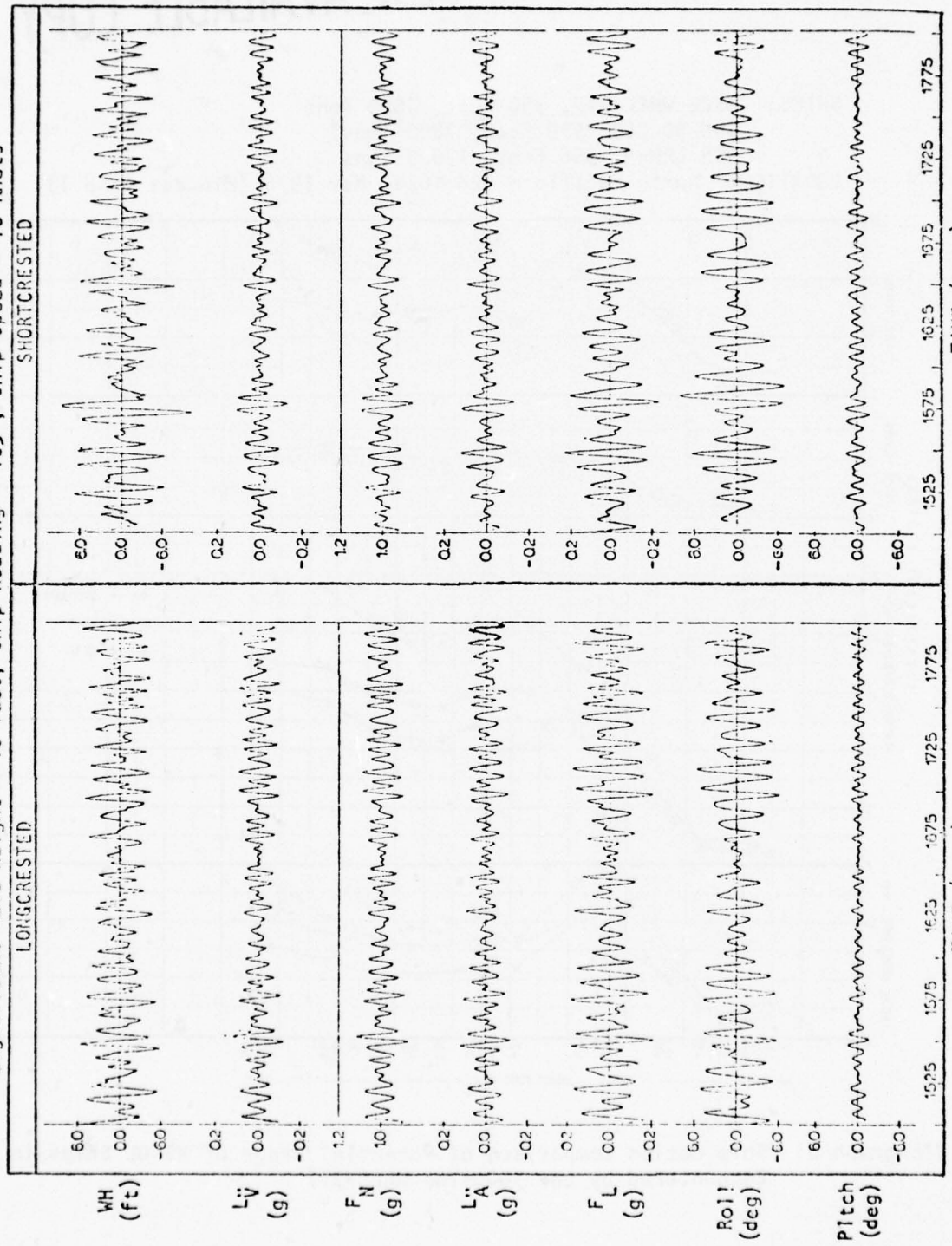
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SHIPS: USCG WHEC-717, 350 Feet, 3000 Tons
USN DD 963, 529 Feet, 7800 Tons
USN LPH-9, 556 Feet, 17000 Tons
LOCATION: North Pacific - 42N 162W, May 1976 (Hincast Case 1)



Viewgraph 8: Ship Motion Comparison of Potential Range of VSTOL Ships in Storm Encountered by the 3000-Ton WHEC-717

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Viewgraph 9: Sample Wave Height, Pitch, Roll, Acceleration, and Motion-Induced Force Time Histories for DD 963 in Longcrested and Shortcrested Seas

OBJECTIVES OF TRIALS

1. GUAM: A) COLLECT SHIP MOTIONS THAT LIMIT AIRCRAFT OPERATIONS

   B) EVALUATE ANTI-ROLL TANK

2. RALEIGH: A) COLLECT SHIP MOTIONS THAT LIMIT AIRCRAFT OPERATIONS, AV8-A

3. BOWEN: A) MEASURE AND RELATE SHIP MOTIONS TO DEGREE OF DIFFICULTY OF HELICOPTER OPERATIONS IN PREVAILING SEAS, SH-2F

Viewgraph 10: Objectives of Some Recent Ship/Aircraft Interface Trials

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TRIAL RESULTS

2. RALEIGH: A) NONE, SEAS TOO MILD

3. BOWEN: A) HELICOPTER PILOTS LAND AT HIGHER RELATIVE SHIP MOTIONS ON DESTROYER THAN ON GUAM

B) LANDINGS AS WITH HARRIERS ON GUAM ARE MORE DIFFICULT THAN TAKEOFFS

C) PILOTS ALSO ATTEMPT TO TIME THEIR OPERATION TO OCCUR DURING SHIP MOTION LULLS

D) FOR A GIVEN WIND ENVELOPE THERE EXISTS A VERY LARGE VARIETY OF SHIP RESPONSES THAT ARE NOT NECESSARILY OBSERVED DURING THE TRIALS WHICH ESTABLISH THE ENVELOPE

E) BOTH ROLL AND PITCH AND THEIR RESPECTIVELY ASSOCIATED LATERAL AND VERTICAL ACCELERATIONS BOTHER PILOTS

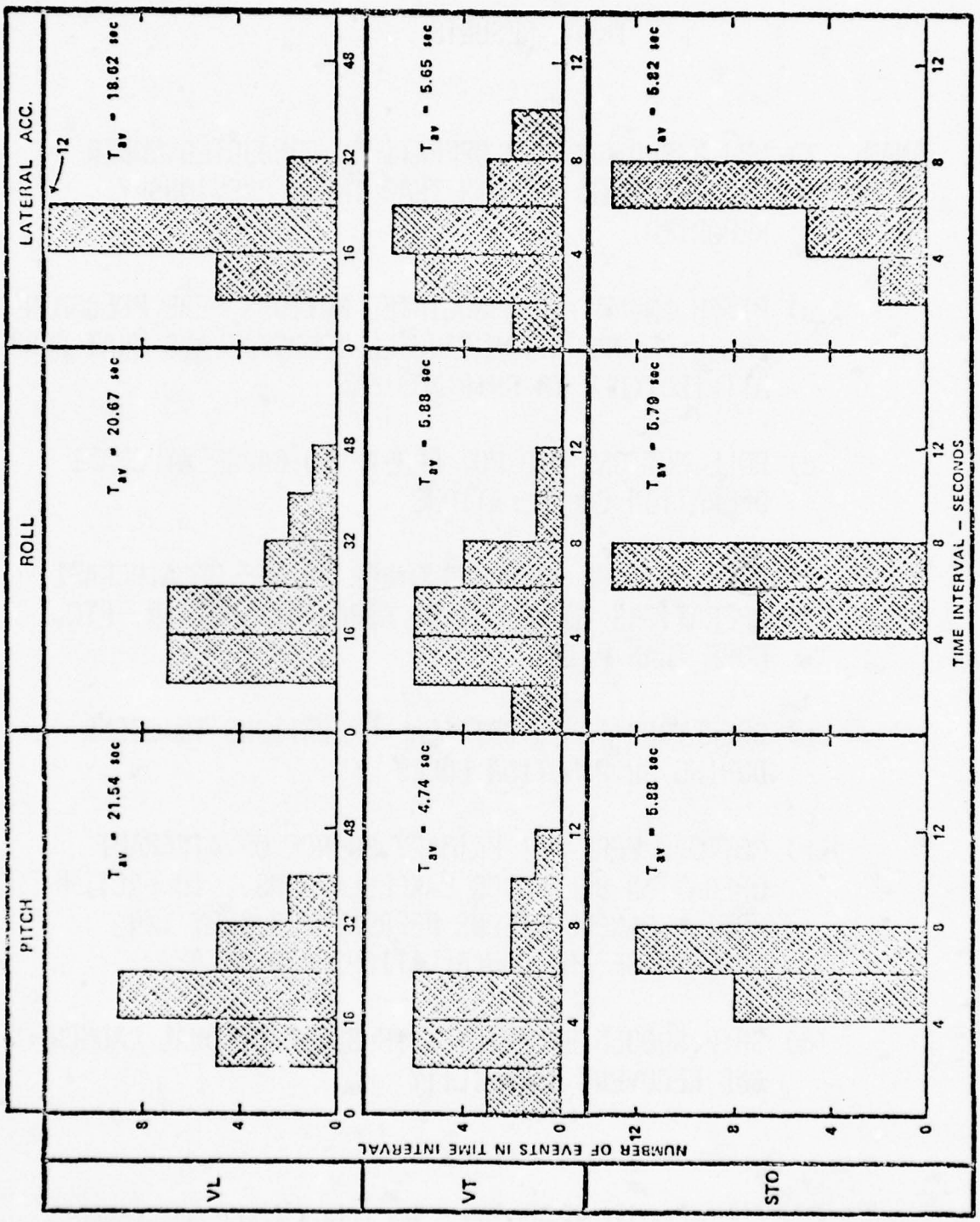
Viewgraph 11: Results of LPD/AV8-A, FF 1078/SH-2F Interface Sea Trials

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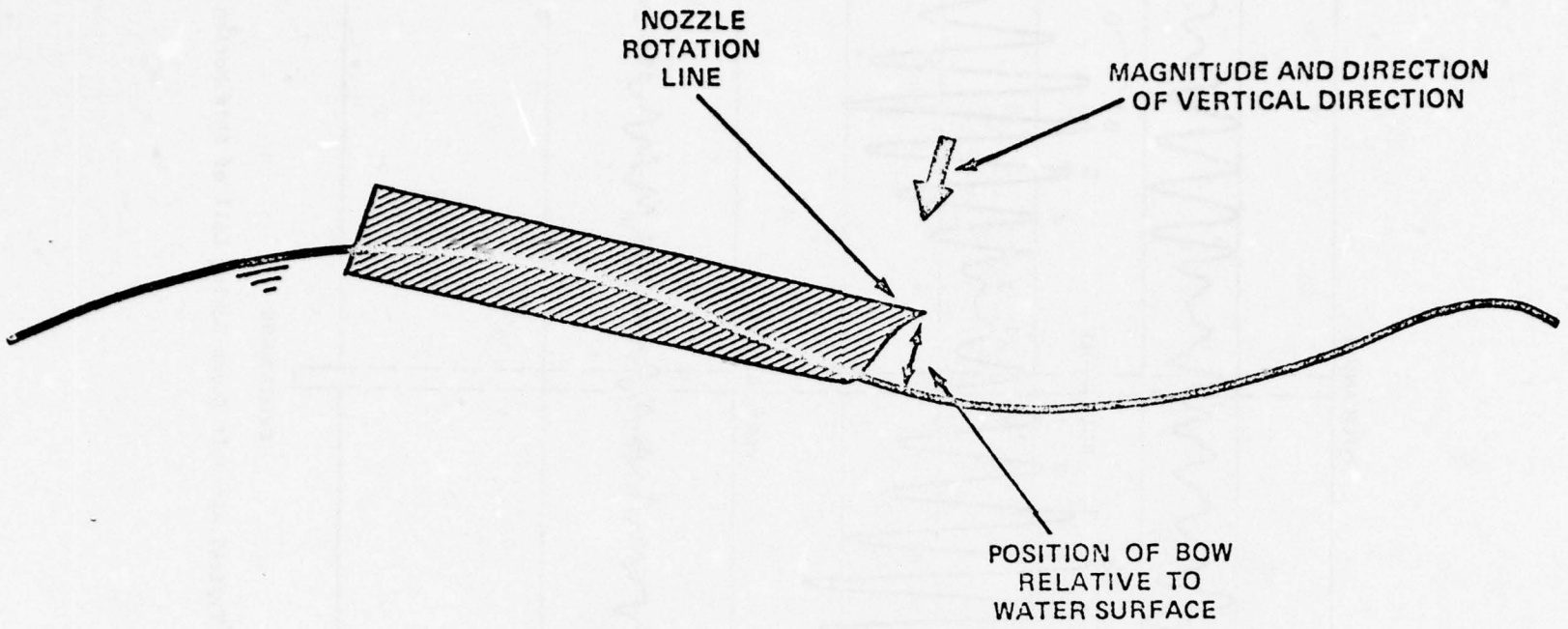
TRIAL RESULTS

1. GUAM:
   - A) LPH BASED HARRIER OPERATIONS CONDUCTED UNDER ROUGHER SHIP MOTIONS THAN THOSE PREVIOUSLY REPORTED
   - B) PITCH AND PITCH ASSOCIATED MOTIONS WERE PREDOMINANT CAUSE OF OPERATION CANCELLATIONS/DELAYS THAT WERE ATTRIBUTABLE TO SHIP MOTIONS
   - C) ROLL MOTIONS DID NOT APPEAR TO CAUSE AIRCRAFT OPERATION CANCELLATIONS
   - D) ROLL MOTIONS BOTHERED OTHER PHASES OF AIRCRAFT OPERATIONS (MOVEMENT OF AIRCRAFT, REPAIR, ETC.) MORE THAN PITCH
   - E) OPERATORS TIMED CRITICAL OPERATIONS TO OCCUR DURING SHIP MOTION LULLS
   - F) MOTIONS WERE NOT PRIMARY SOURCE OF AIRCRAFT OPERATION DELAYS OR CANCELLATIONS. IN FACT, MOTION CANCELLATIONS REPRESENTED ONLY 1/4 OR LESS OF ALL CANCELLATIONS AND DELAYS
   - G) SHIP SHOULD BE BUILT WITH BIDIRECTIONAL LAUNCH AND RECOVERY CAPABILITY

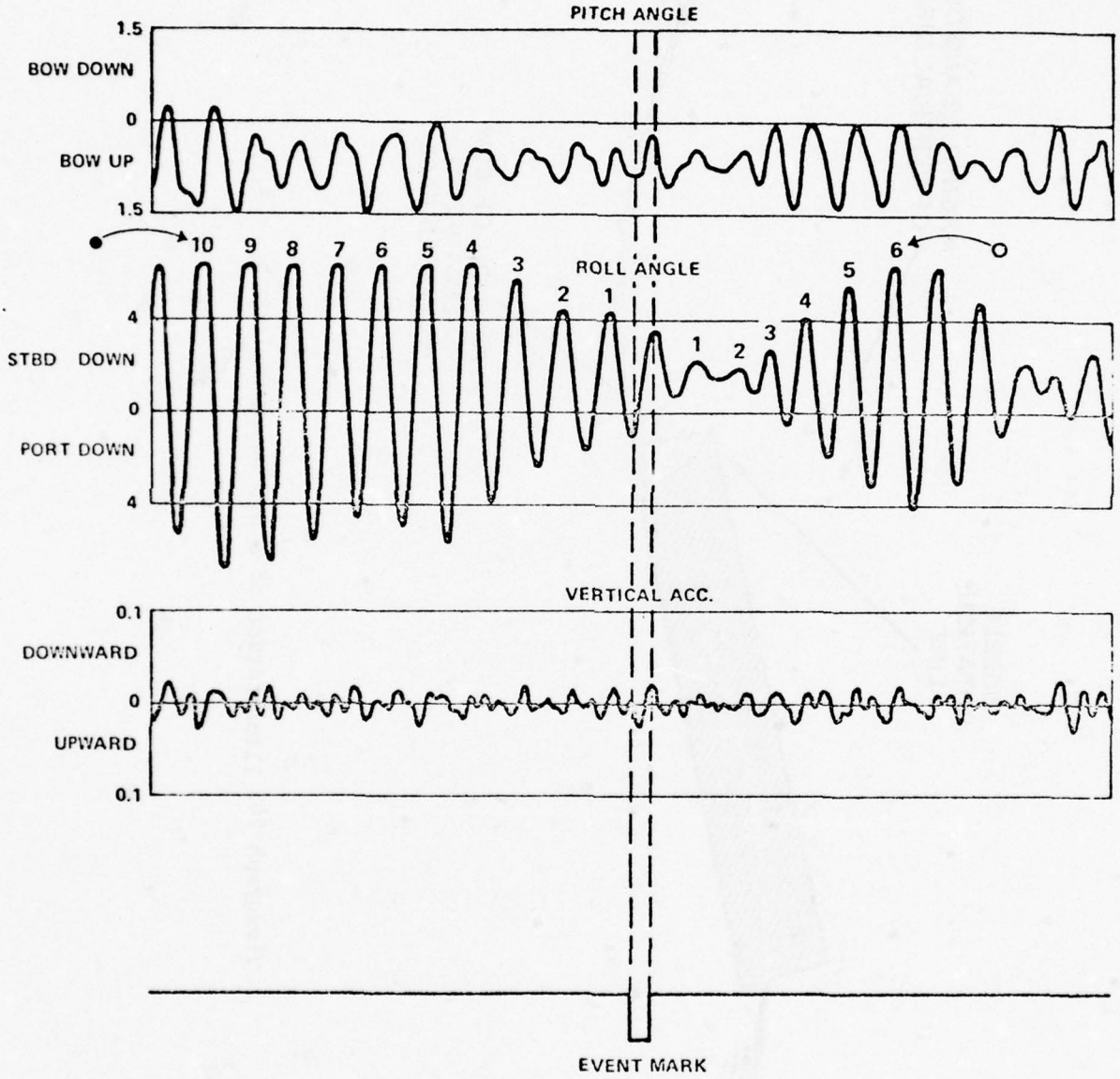
Viewgraph 12: Results of LPH/AV8-A Sea Trials (1972-73), Summary



Viewgraph 13: Event Time Length Summary for Three Types of Aircraft Events

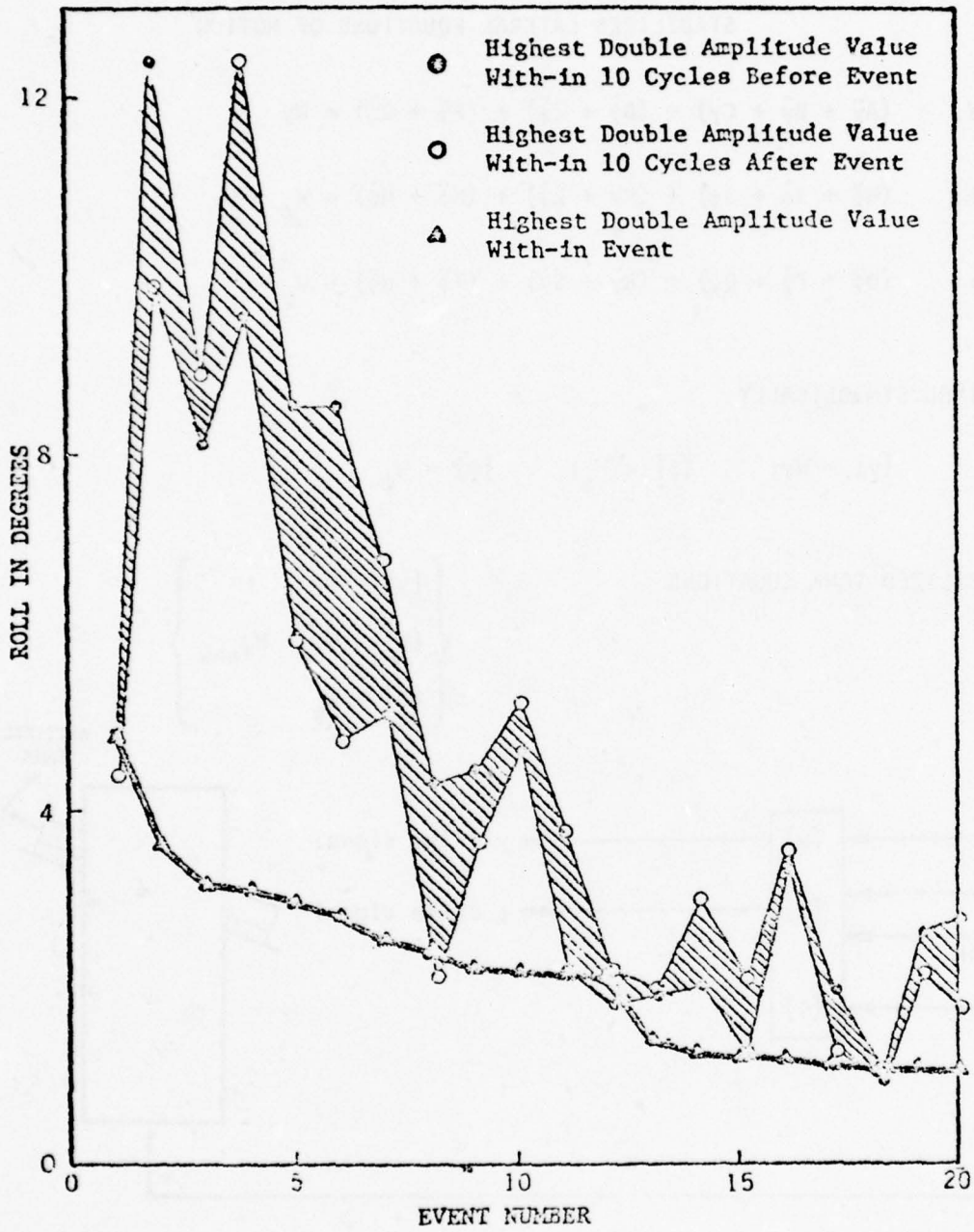


Viewgraph 14: Illustration of a STO Bow Down Launch



Viewgraph 15: Typical Aircraft Event During Lull of Ship Motion

AIRCRAFT EVENT SHIP MOTION DATA ORDERED BY DOUBLE AMPLITUDE VALUES



Viewgraph 16: Short Takeoffs (STO's) Related to Ship Motion Lulls

STABILIZED LATERAL EQUATIONS OF MOTION

SWAY: $(A\ddot{y} + B\dot{y} + Cy) + (D\ddot{\phi} + E\dot{\phi}) + (F\ddot{\psi} + G\dot{\psi}) = Wy$

ROLL: $(H\ddot{\phi} + I\dot{\phi} + J\phi) + (K\ddot{y} + L\dot{y}) + (M\ddot{\psi} + N\dot{\psi}) = W_{\phi} + W$

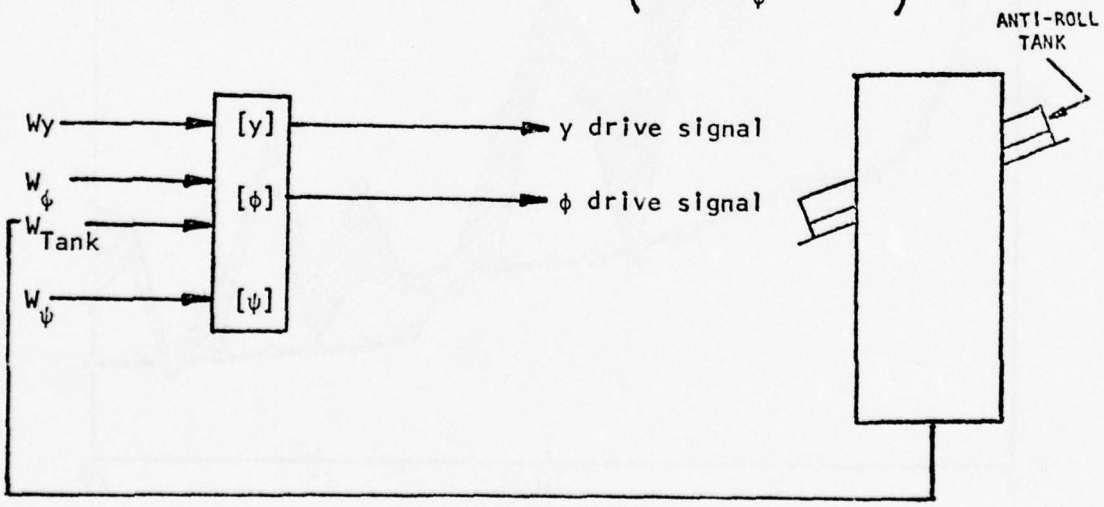
YAW: $(O\ddot{\psi} + P\dot{\psi} + Q\psi) + (R\ddot{y} + S\dot{y}) + (T\ddot{\phi} + U\dot{\phi}) = W_{\psi}$

DEFINED SYMBOLICALLY

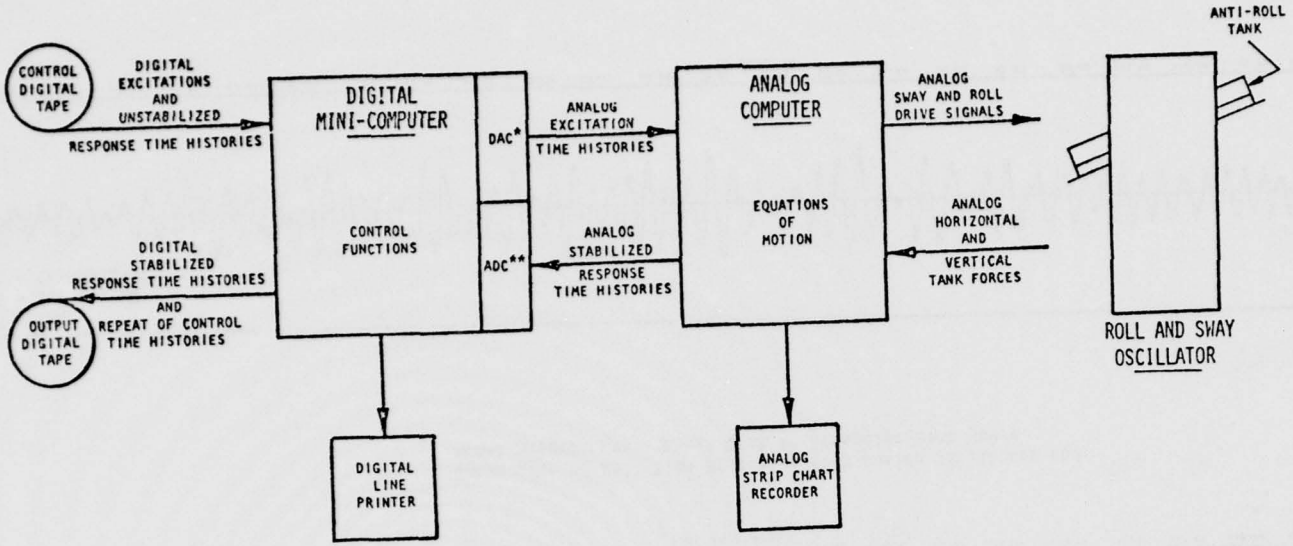
$[y] = Wy; \quad [\phi] = W_{\phi}; \quad [\psi] = W_{\psi}$

STABILIZED TANK EQUATIONS

$$\left\{ \begin{array}{l} [y] = Wy \\ [\phi] = W_{\phi} + W_{Tank} \\ [\psi] = W_{\psi} \end{array} \right\}$$



Viewgraph 17: Anti-Roll Tank Stabilized Ship Math Model

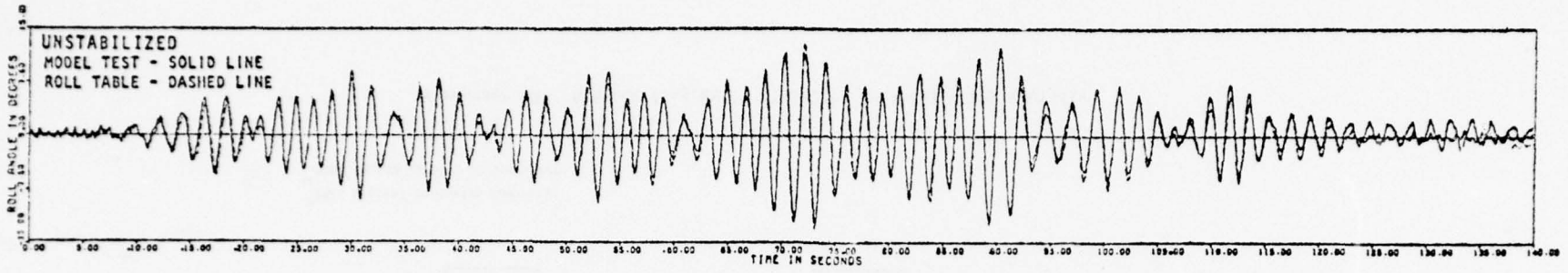


*DAC: Digital to Analog Conver

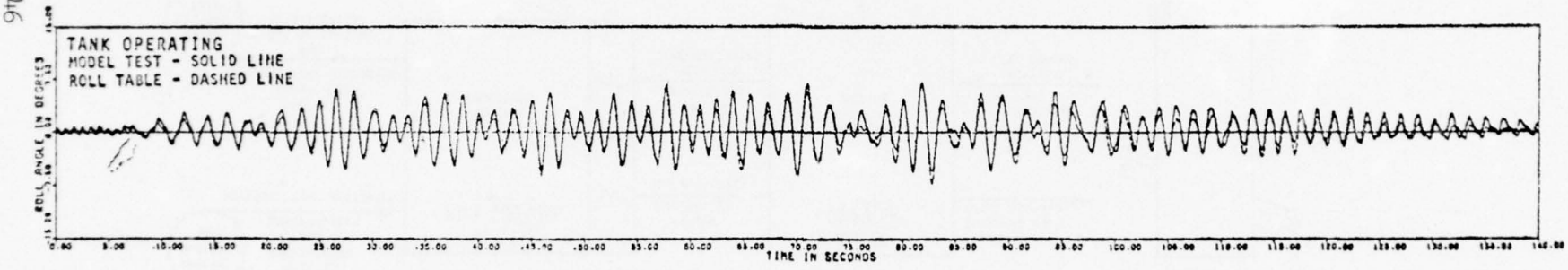
**ADC: Analog to Digital Conv

Viewgraph 18: A Block Diagram of DTNSRDC's Anti-Roll Tank Facility

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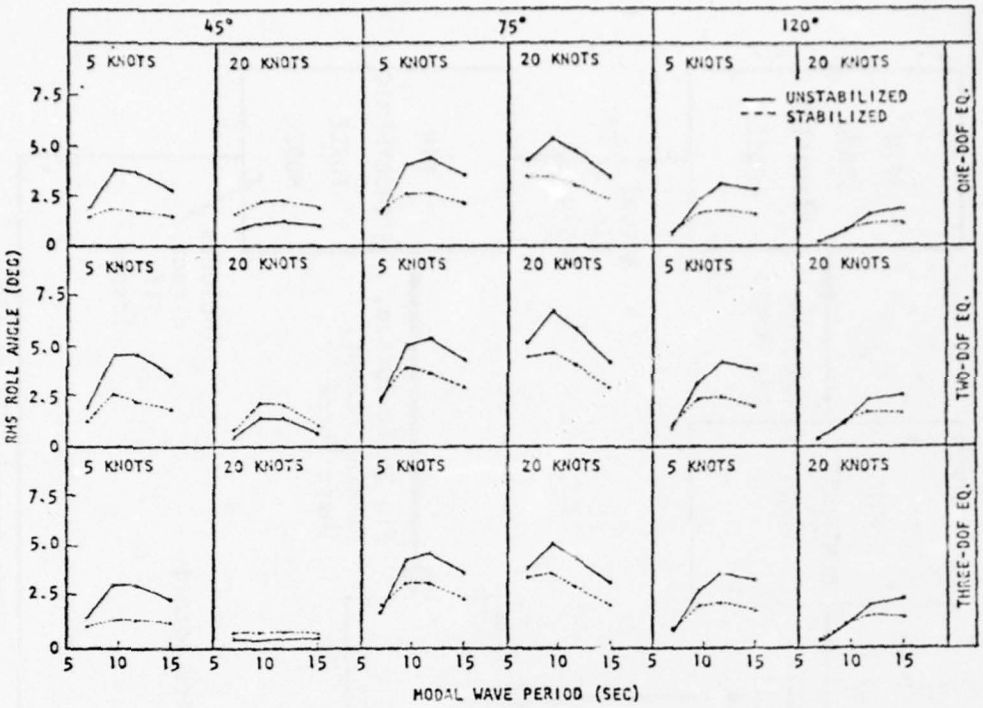


Comparison of Roll Time Histories from Analog Simulation and
Model Experiments without Tank in Irregular Beam Waves

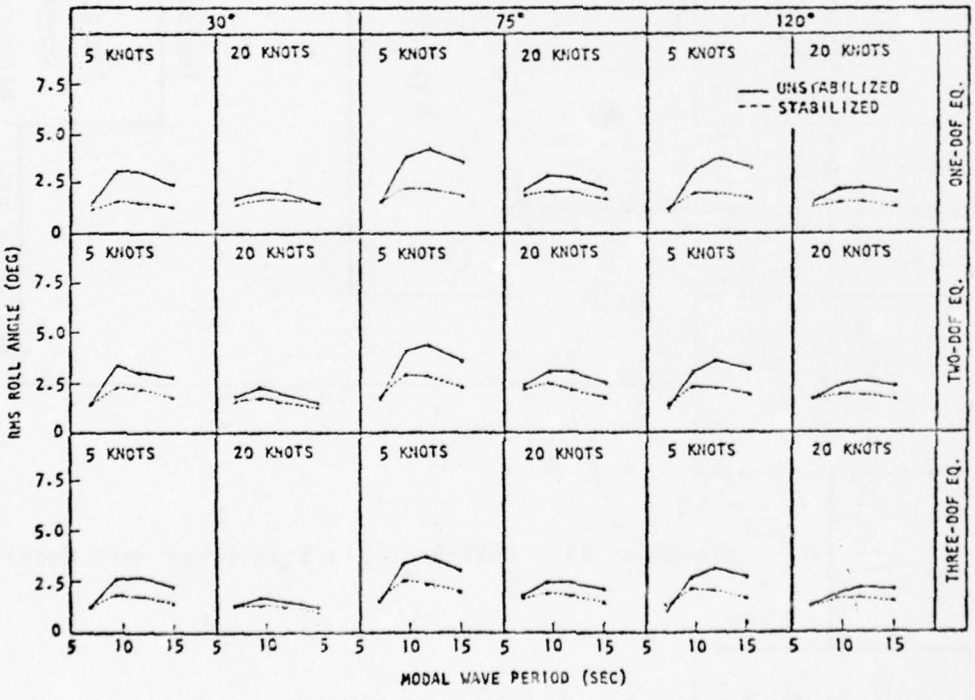


Comparison of Roll Time Histories from Roll Table and
Model Experiments with Tank in Irregular Beam Waves

Viewgraph 19: Experimental Validation of DTNSRDC Anti-Roll Tank Facility

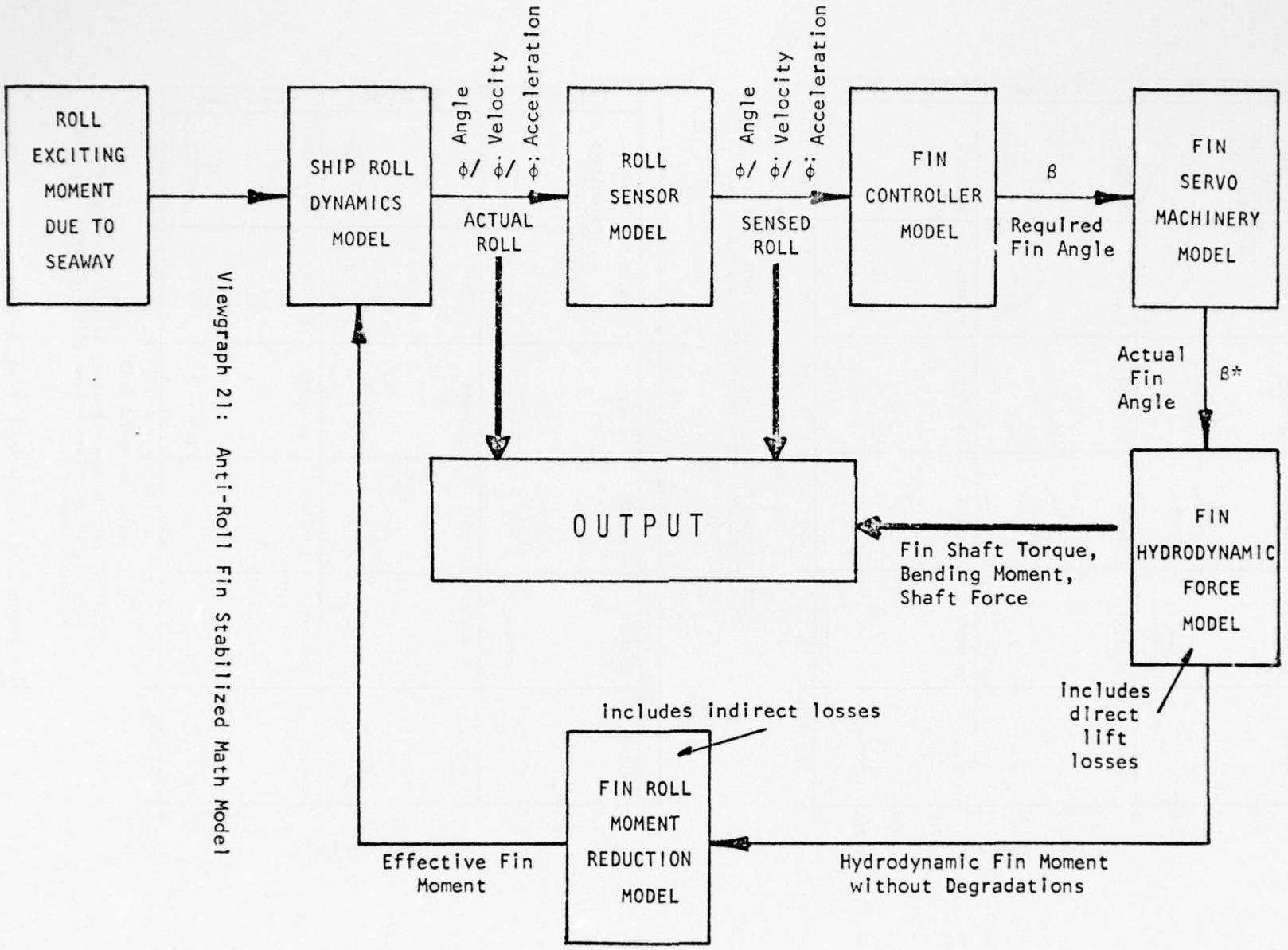


Roll Motions in Long Crested Seas with a Twelve Foot Significant Wave Height (Bretschneider Two-Parameter Spectra)



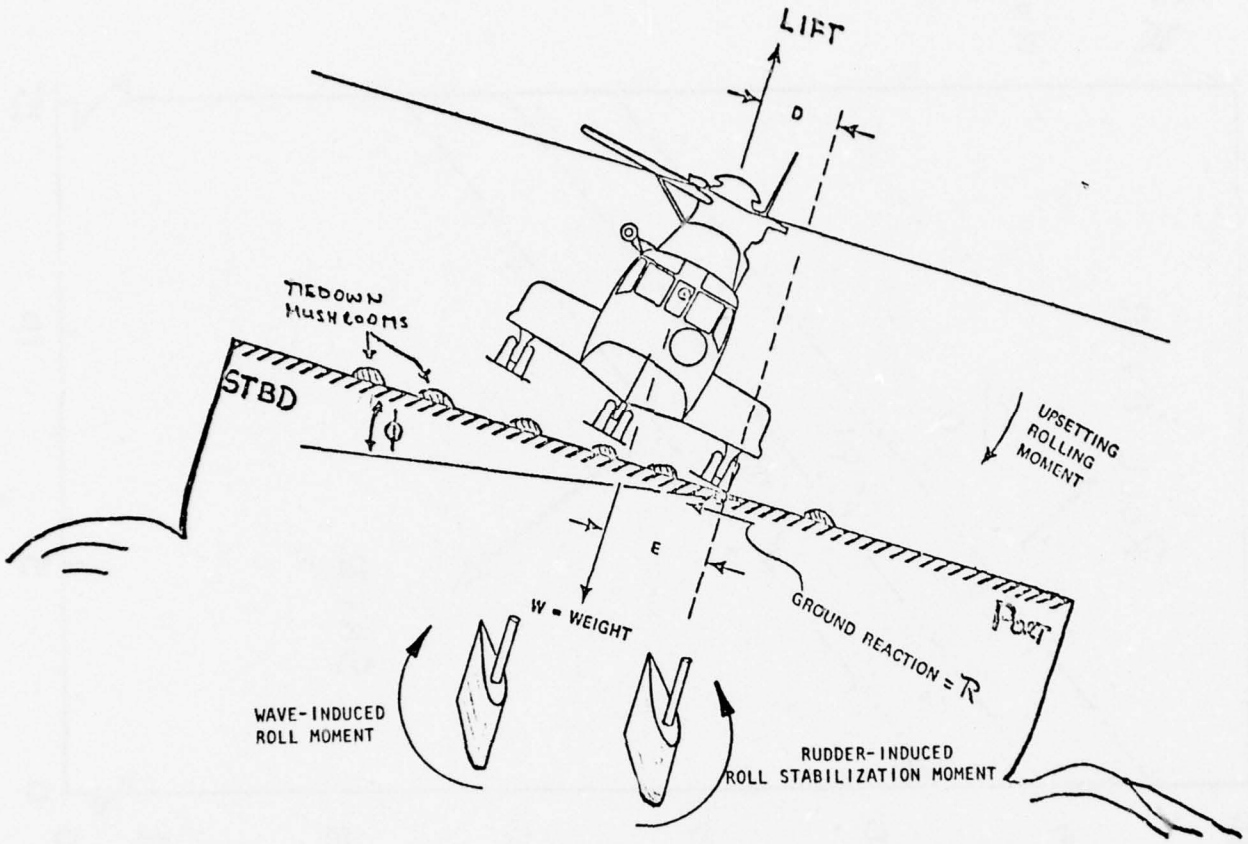
Roll Motions in Short Crested Seas with a Twelve Foot Significant Wave Height (Bretschneider Two-Parameter Spectra)

Viewgraph 20: Anti-Roll Tank Results



Viewgraph 21: Anti-Roll Fin Stabilized Math Model

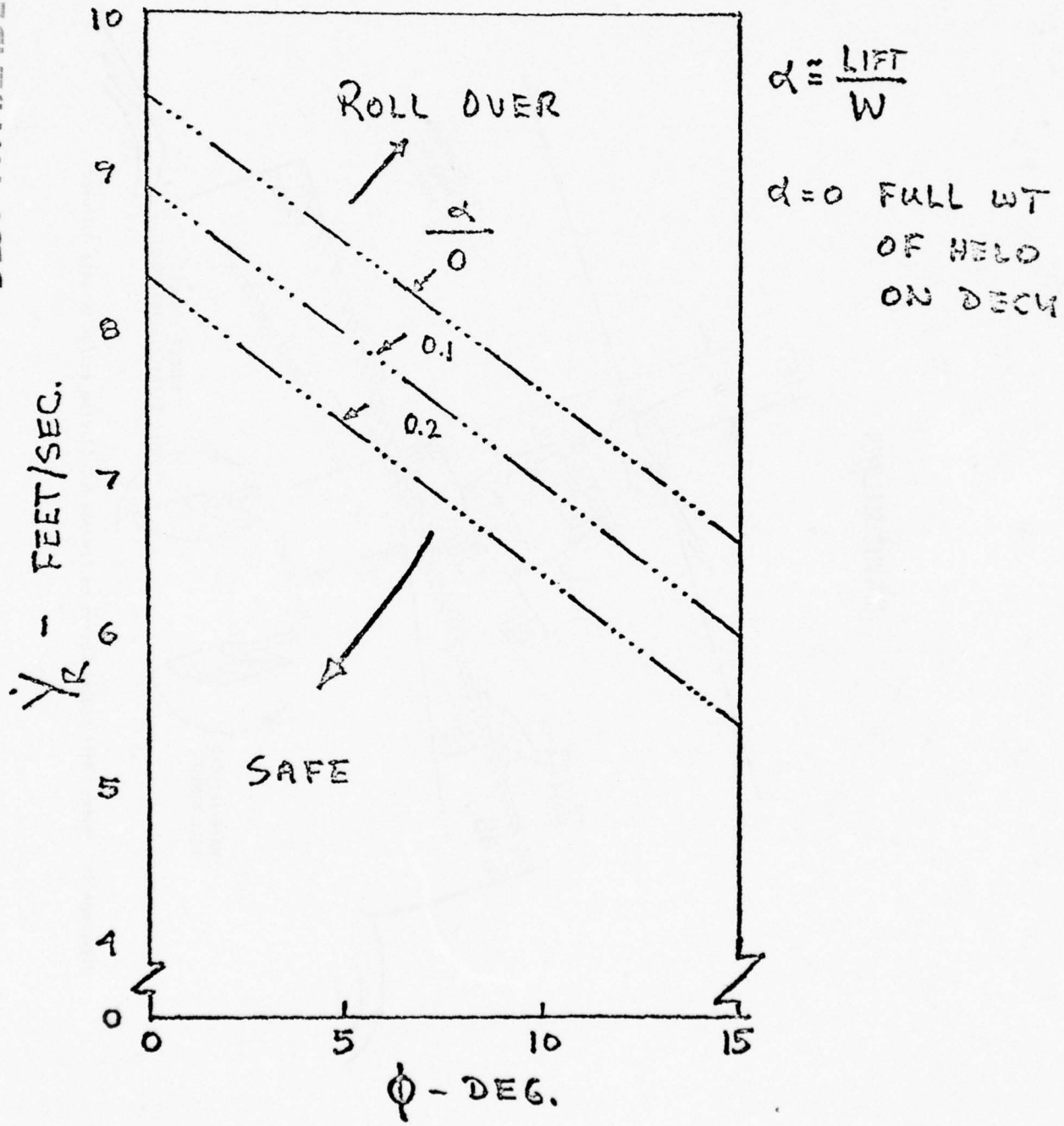
DYNAMIC ROLLOVER



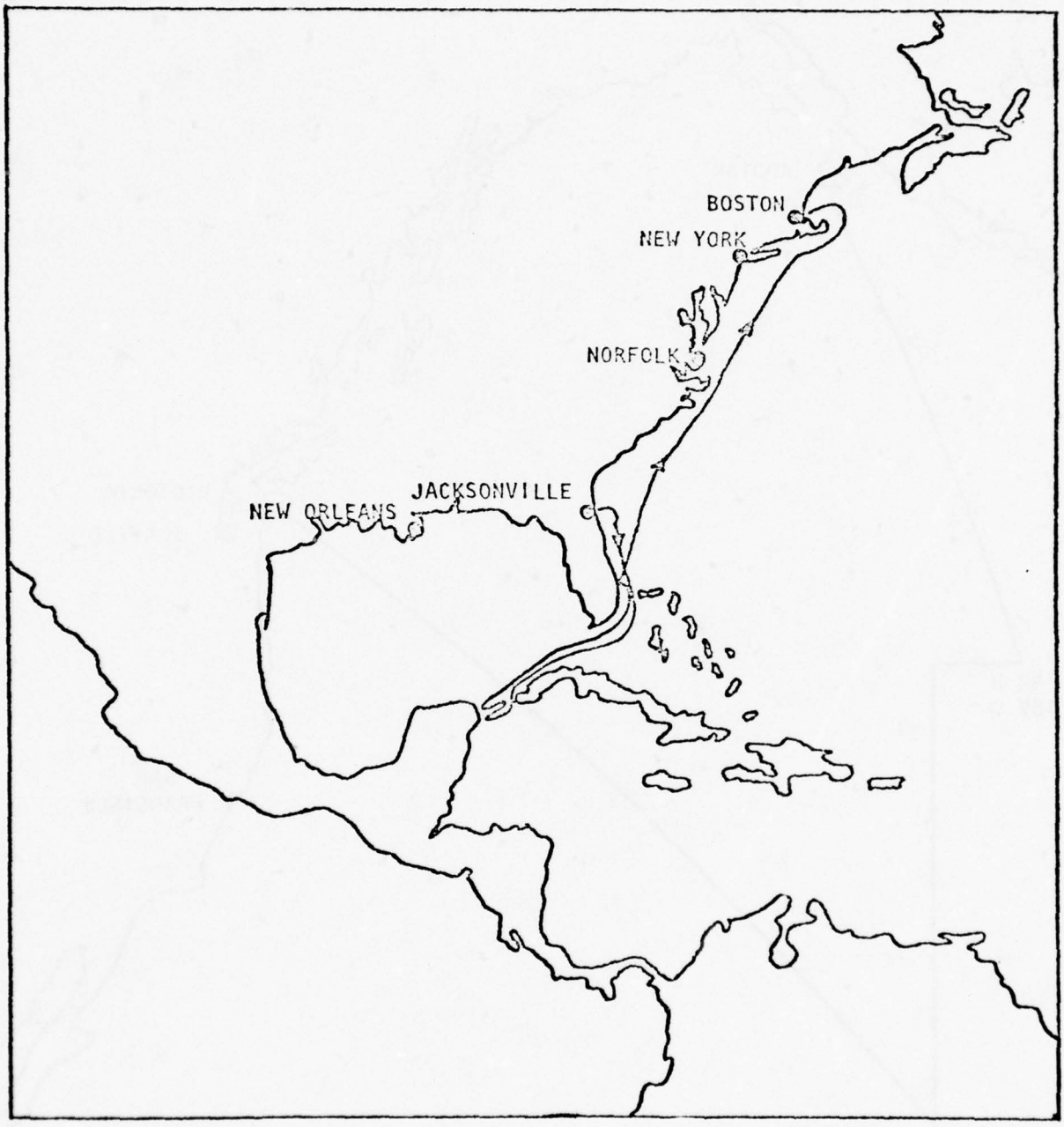
Viewgraph 22: Rudder Roll Stabilization to Prevent A/C Sliding and/or Dynamic Rollover

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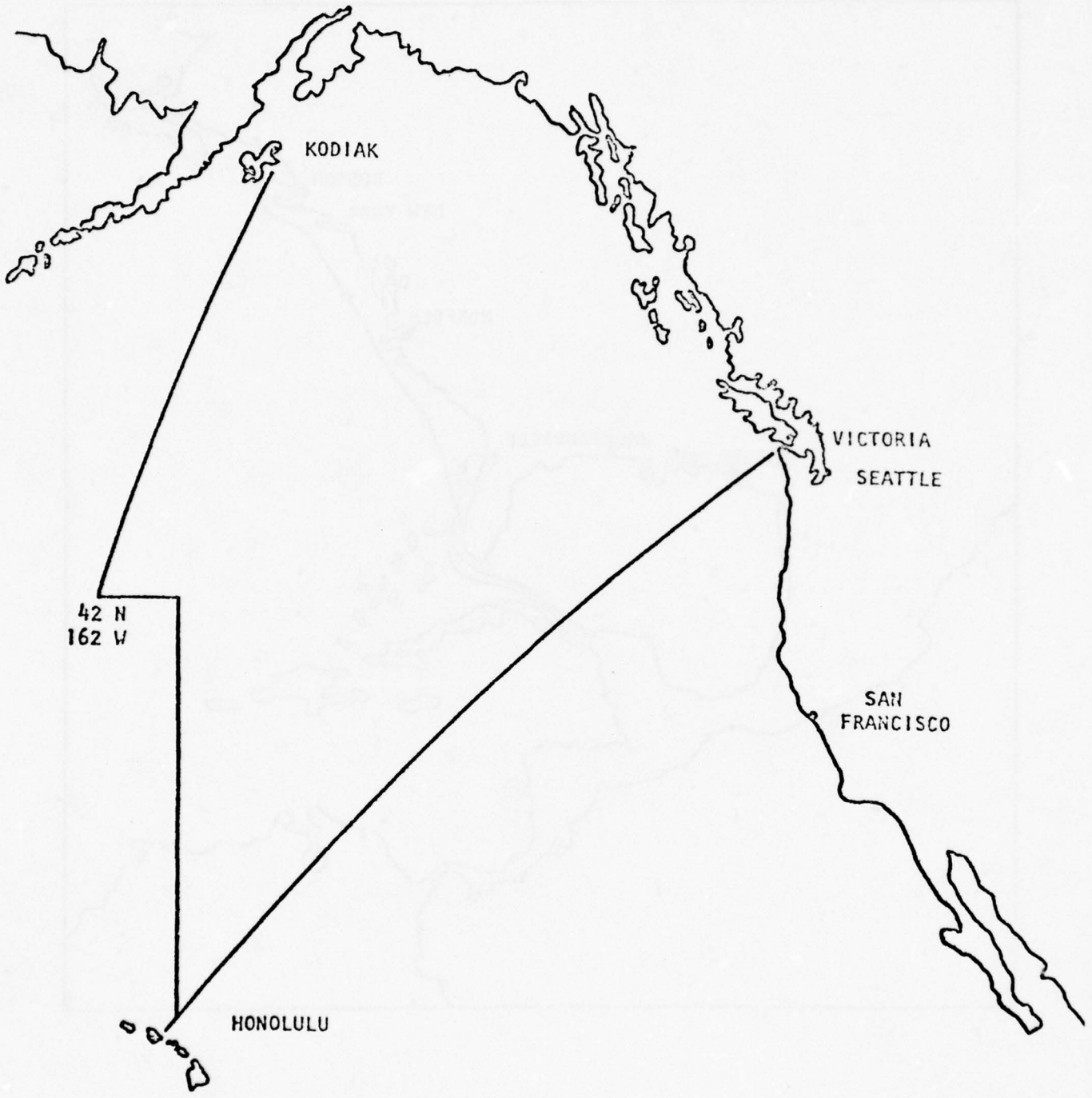
APPROXIMATE RELATION BETWEEN
RELATIVE LATERAL VELOCITY,
SHIP ROLL AND ROLLOVER



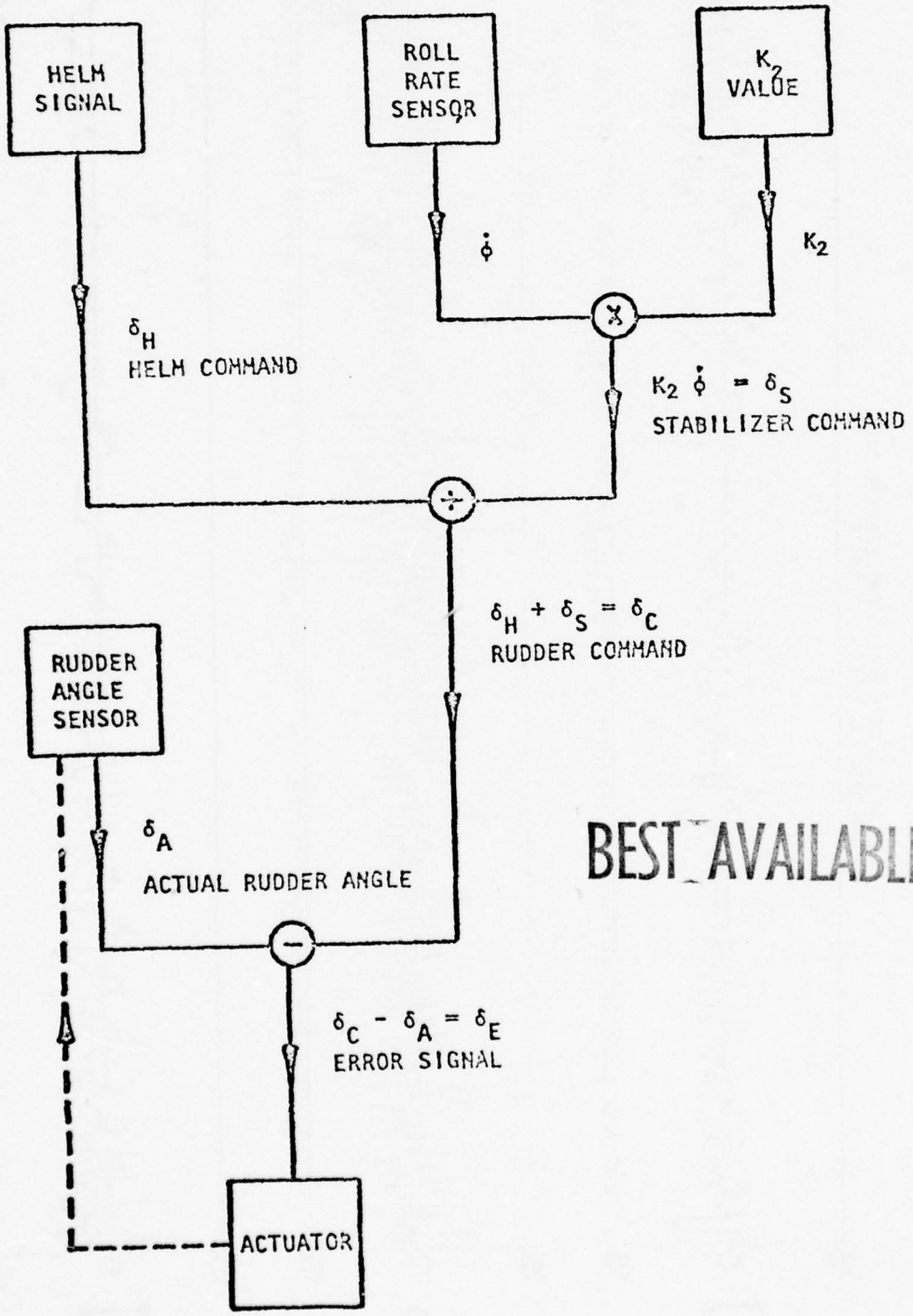
Viewgraph 23: Regions Where Dynamic Rollover May Occur



Viewgraph 24: October 1975 Deployment with Rudder Stabilization/H-3F on WHEC-715 *Hamilton*



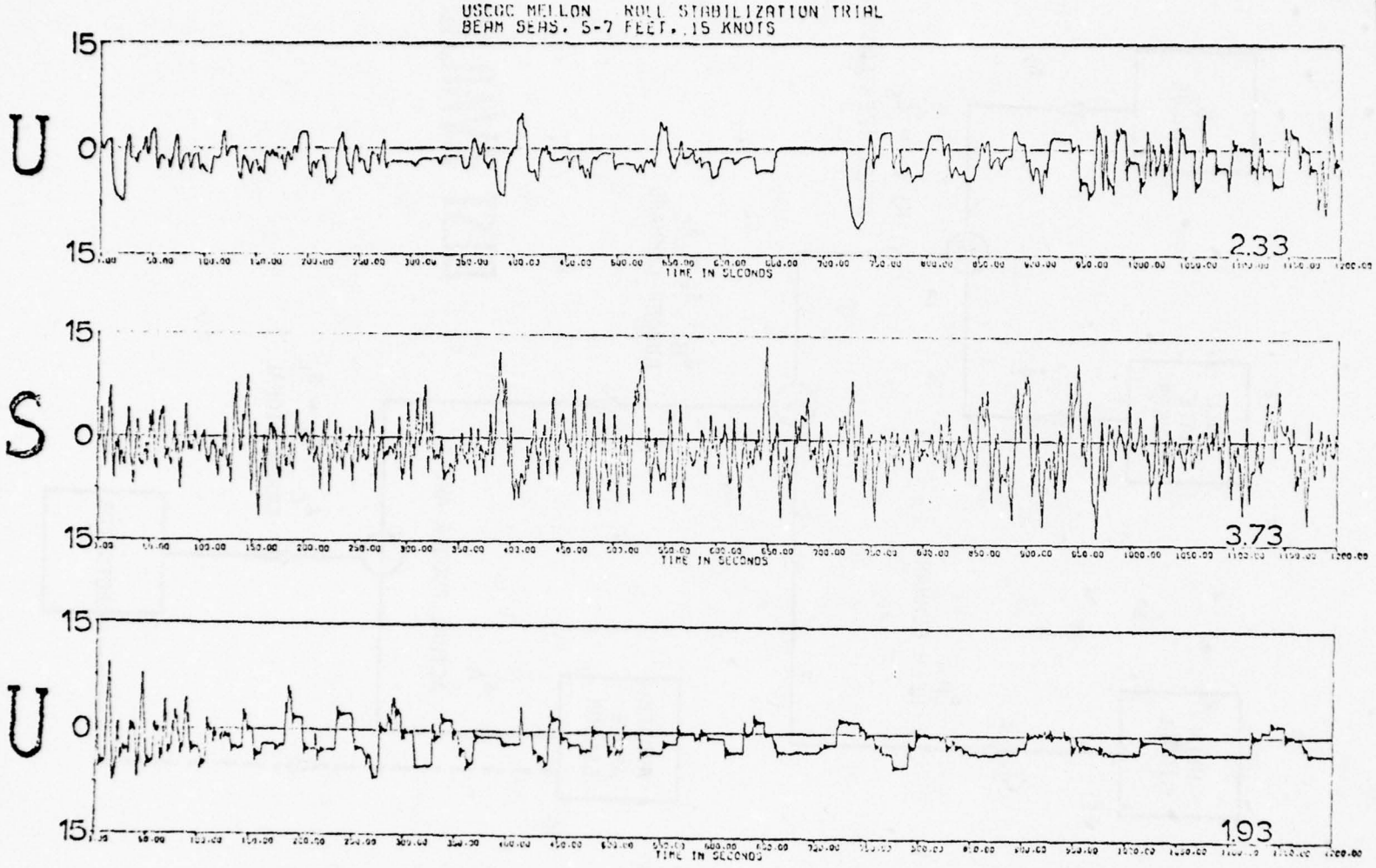
Viewgraph 25: May-June 1976 Deployments of Rudder Stabilization on WHEC-717 *Mellon*



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Viewgraph 26: Rudder Roll Stabilization System

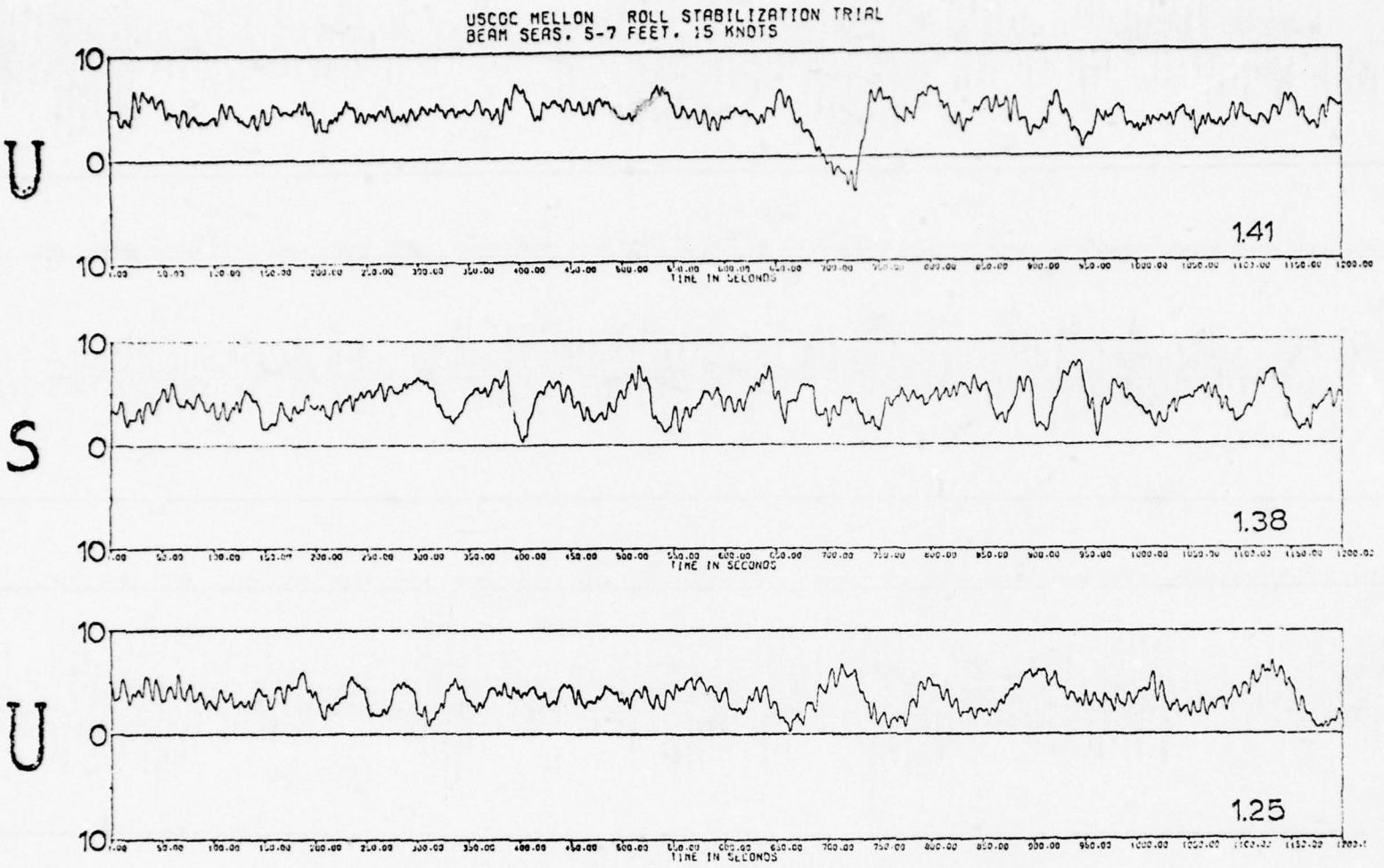
RUDDER



Viewgraph 27: Rudder Activity in the Unstabilized and Stabilized Mode

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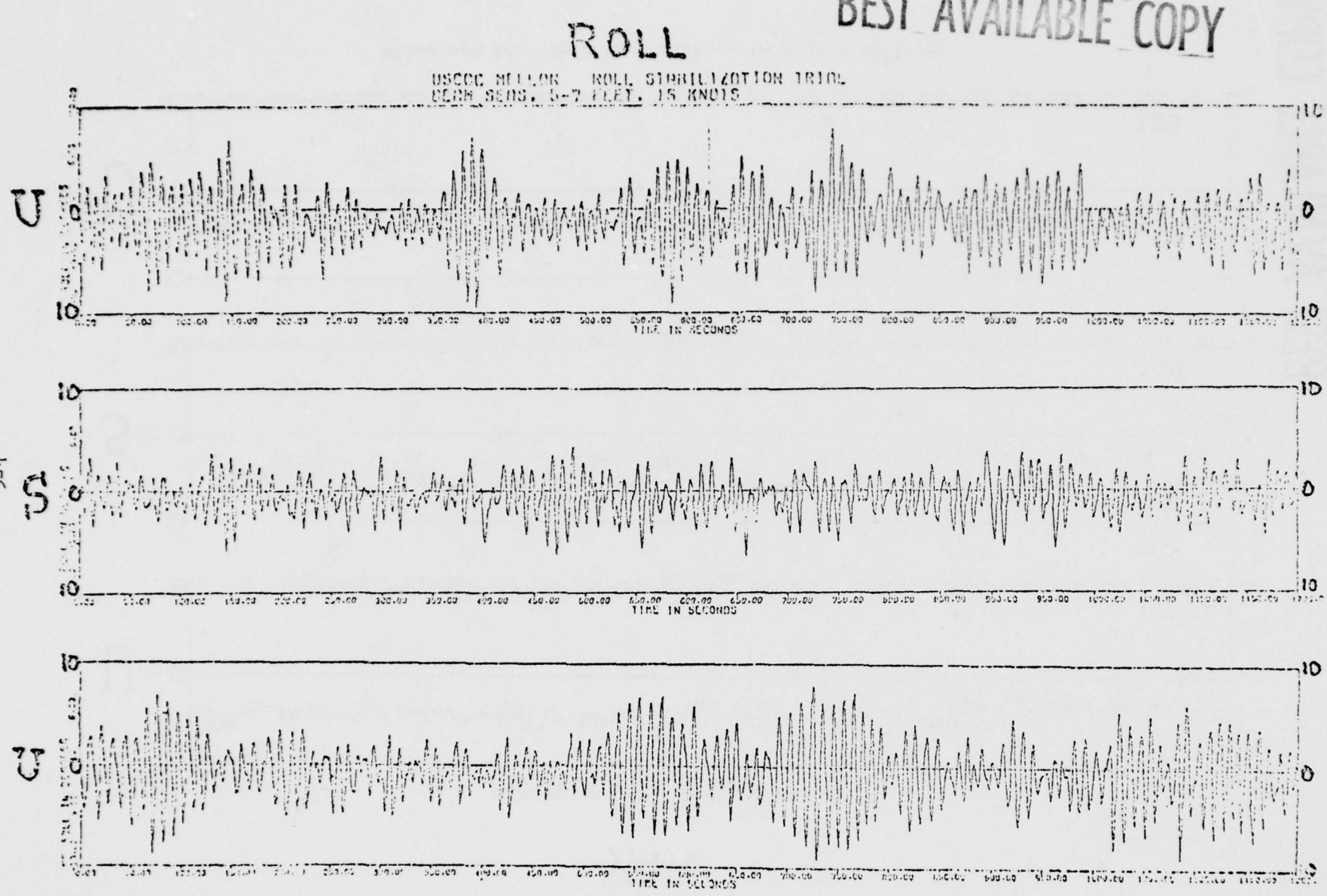
YAW



Viewgraph 28: Ship Yaw Response to Rudder Activity

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Viewgraph 29: Unstabilized and Rudder Stabilized Roll Motion

FUTURE PLANS

A) USCG

B) U S NAVY

USCG PLANS - PROPOSED

STEP 1. PERFORM OP EVAL ON 2 SHIPS,
ONE EAST COAST, ONE WEST
COAST/HONO.
PREFERENCE: USCG HAMILTON
MELLON

STEP 2. BACKFIT HAMILTON CLASS,
BUILD, SUBCONTRACT 11 - 12
COMPLETE SYSTEMS AT
COST OF 12.8 K$ PER UNIT

STEP 3. INVESTIGATE APPLICATION OF RUDDER STABILIZER ON USCG 210' AND OTHER HULLS; ICEBREAKERS, CUTTERS.

STEP 4. DEVELOP SPEC'S TO INCLUDE RUDDER ROLL STABILIZATION ON NEW 270'.

STEP 5. MEASURE ROLL STABILIZER PERFORMANCE DURING SHIP/ HELO OPS IN ALASKAN WATERS.

DISCUSSION

Vincent Zimnoch: Some time ago we talked about RAO's for waves moving in different directions. Do you have any comment on that?

Erich Baitis: The RAO's are in the report, therefore for sake of time expediency I would prefer to refer you to that.

SEAKEEPING CONSIDERATIONS IN THE EMPLOYMENT OF V/STOL ON NAVAL SHIPS

by LCDR S. R. OLSON, USN
Center for Naval Analyses

Paper Presented at the NAVY/NASA
V/STOL Flying Qualities Workshop

26-28 April 1977
U.S. Naval Postgraduate School
Monterey, California

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The development of the Vertical/Short Take-Off and Landing aircraft will significantly alter the nature of the U.S. Navy in the next 20 years. Because of the broad impact of V/STOL on future Naval forces and tactics, it is obvious that the V/STOL development community must remain constantly aware of their interface with the fleet. An important consideration in this regard is the compatability of Naval ships as V/STOL support platforms, and the ship motions that V/STOL aircraft must contend with.

This paper will briefly describe a methodology that is useful in evaluating the impact of motion criteria such as the maximum ship motion allowable during V/STOL land/launch evolutions. It is hoped that this methodology will lead the V/STOL development effort to consider ship motion itself as a design parameter. Ships, even 3500 ton destroyers, are no longer bound to endure excessive seaway motions. There are design alternatives that can significantly reduce ship motion if the need can be properly stated. Thus, early considerations of the ship motion environment during V/STOL development can be an important factor in the design of V/STOL support platforms.

The methodology for a seakeeping evaluation is a relatively simple one. It requires estimates of the motions of a ship in various seaways. As would be expected, these motions are dependent on a ship's design and speed, and the heading of the sea relative to the ship, as well as the characteristics of the seaway itself. If we then identify allowable motion limits based on the ship's mission, a reasonable seakeeping assessment can be calculated. This paper will describe the general approach used to carry out these calculations.

Before proceeding with a general discussion of the approach, it is worthwhile to provide some definitions:

- Significant wave height. A commonly used oceanographer's term that is defined as the average height of the highest one-third waves present in a seaway. It is thought by many to be the height normally "seen" by mariners making wave height observations. Wave height is itself defined as the vertical distance from the crest of a wave to the bottom of the succeeding trough.

- Significant. The term significant is also applied to ship motions in the same manner as it is for waves. Thus, the significant roll is the average of the greatest one-third rolls.

- Single amplitude. The one-way displacement from the normal rest position. For roll, this is the same as the phrase "vertical-to-out."

• Double amplitude. The peak-to-peak displacement. It is equivalent to twice the single amplitude.

• Heading angle. This paper adapted the convention used by the Naval Ship Research and Development Center where the heading angle is equivalent to the angle of incidence between the heading of the ship and the direction in which the predominant sea is moving. Thus, a 000° heading angle is a following sea, while a 180° heading angle is a head sea.

• Modal wave period. The period of the waves associated with the maximum spectral energy of a seaway.

• Limiting wave height. The maximum significant wave height in which a ship can operate without violating a specified criterion. This is a function of ship design, ship speed, heading angle, and modal wave period.

• Simple criterion. A simple criterion is herein defined as a seakeeping criterion whose evaluation is a function of a single motion parameter. E.g., ten degrees average roll is a simple criterion.

• Complex criterion. A complex criterion is herein defined as a seakeeping criterion whose evaluation is dependent on two or more motion parameters. For example, a criterion might be stated as a combination of conditions, such as 7 ft/sec velocity at the flight deck, and 3° single amplitude pitch, where both of these conditions must be exceeded before the criterion itself is violated.

A seakeeping evaluation requires a set of selected seakeeping criteria, i.e. explicit statements of motion thresholds, such as 12 degree average roll, which reflect considerations of personnel or system effectiveness. There may be many such criteria that reflect a variety of V/STOL considerations.

A simple computer program has been written to evaluate these criteria for a specific ship design and at discrete combinations of ship speed, heading, and modal wave period. The program identifies the criterion that is violated before all others in each case and estimates the significant wave height at which that criterion is exceeded. This concept might best be understood by considering the "seakeeping matrix" shown in figure 1. The matrix shows the ship represented at the center with concentric speed bands of 5, 10, 15, 20, and 25 knots. Also shown are arcs, in 15 degree increments, which represent the heading of the sea. Estimates of the ship motion are used to evaluate every criterion in each cell of the matrix and thus provides a comprehensive seakeeping assessment for a ship. An individual matrix may also be displayed as a three dimensional seakeeping contour.

We can then combine this information with oceanographic data reflecting frequencies of observed sea conditions in a specified environment. Then, using straightforward assumptions regarding ship speeds and headings we can calculate the percent of time that a ship can expect to operate in the environment without violating any criterion.

The foregoing description is best understood by observing the computer program output.

Table 1 shows the first form of output that consists of two matrices and explanatory information. The top matrix contains codes as a function of ship speed and heading of the seas. These codes identify the limiting seakeeping criterion as defined in the list immediately below the matrix. The bottom matrix identifies the significant wave height (in feet) at which the specified criterion (from the top matrix) is being exceeded. Thus, the two matrices are complementary. The top matrix explains what criterion is being exceeded first, and the bottom matrix identifies the level of ocean wave activity at which that criterion is exceeded. (The maximum wave height is limited by the variable WAVMAX (i.e., 32 feet). These tables are unique for the specified ship, modal wave period of the sea, and the selected criteria actually being considered, as identified in the title heading at the top of the page.

It should be noted that matrices similar to that in Table 1 can be quite useful in optimizing a ship's seakeeping characteristics for V/STOL employment. If reasonable seakeeping criteria for V/STOL can be stated, we can estimate how significant these criteria are when compared to other seakeeping considerations. These criteria thus become a useful tool in the ship design process.

Figure 2 shows the second form of output, the three dimensional seakeeping contour. A contour is actually a picture of the lower matrix presented in Table 1. Thus, it too is unique to a specified ship, modal wave period and the selected criteria.

A contour represents the seakeeping qualities of the ship in seas from zero to 32 feet and at speeds from zero to 28 knots, and is visualized in the following manner. Consider that the ship is proceeding from left to right,* and that a specific direction of the sea is represented by its corresponding radial directed toward the center of the contour plot. Consider also that speed is represented by concentric circles in the contour. Thus, the center of the contour represents

*The contour is symmetric about this left-to-right axis.

a speed of zero knots, while the outer radius represents a speed of 28 knots. (A convention adapted in drawing the contours is that, at speeds less then 3 knots, the ship will broach into beam seas.)

The height of the contour reflects the maximum significant wave height, at the particular speed and heading, that the ship can accept without exceeding any of the specified seakeeping criteria. The fuller the contour, the "better" the seakeeping qualities of the ship.

The label on the vertical axis of the contour is the significant wave height in feet. The numbers printed at the edge of the planar axes are idiocyncracies of the computer plotting program. They would indicate the ship speed if the plotter boundaries passed through the center of the contour.

Table 2 shows the third form of output which presents the basic seakeeping box scores for a ship operating in the North Atlantic. These scores are determined by evaluating all of the "Table 1 type" matrices in the light of the expected sea conditions in the environment specified. The numbers reflect the percent of time that the ship can operate in that environment without exceeding any of the criteria. These box scores reflect the following assumptions:

- The probability of encountering a sea at a specific heading angle is equally likely for all headings.

- The speed at which the ship desires to operate is equally distributed at 5, 10, 15, 20, and 25 knots.

This second assumption can easily be relaxed by exploring the effect of speed on the box score and is in fact displayed for the ALL CRITERIA case shown in Table 2.

The random nature of a seaway must of course be recognized when specifying seakeeping criteria. It is fortunate that we can do this rather easily with a statistical approach.

Ship motion amplitudes can be reasonably described by the Rayleigh probability density function, shown in equation 1.

$$f(x)=\frac{X}{E}\exp\left[\frac{-X^2}{2E}\right],\quad o\leq x<oo \qquad (1)$$

$$=o \qquad\qquad x<o$$

where E is the energy of the spectrum. (reference 1)

Thus, once we have identified the ocean wave spectrum of interest, we can calculate the likelihood of occurance for motion of a specific amplitude using equation 2. (reference 1)

$$P\ [X>x] = \exp\left[\frac{-2x^2}{x_{1/3}}\right] \quad (2)$$

where X = a random variable representing the peak excursion in n cycles of ship motion.

x = the motion limit being evaluated

$x_{1/3}$ = the average of the largest one third motion amplitudes observed in n cycles.

$= 4.00 \cdot E$

The significant motion value ($x_{1/3}$) can be estimated using a ship motion computer model.

Table 3 is a convenient form of summarizing statistical constants derived from equation 2. For example, if we believe that we can accept a ship roll of 10° no more than once in 100 motion cycles, our seakeeping criteria for roll is (10/3.03) RMS (root mean square). This RMS value can then be used to calculate estimated sea conditions in which this criterion will be exceeded. Note that the burden is on the V/STOL designer to establish ship motion criteria based on some specified level of risk (e.g., one event in 100), in addition to the peak (or average) motion associated with this risk.

It is worthwhile to observe the significance of the ship motion criteria shown in Table 4. These criteria were used to evaluate four Naval monohulls and a representative 3400 ton Small Waterplane Area Twin Hull (SWATH) design. All of these ships may eventually carry at least two LAMPS helicopters. We can see from Table 5 that there is a large variability in the helicopter compatability of these warships. If similar, or perhaps more restrictive, seakeeping criteria are appropriate for V/STOL, then effectiveness of the V/STOL weapons system may be significantly impaired by platform motion. The Navy might therefore consider new ship designs to improve the seakeeping qualities of V/STOL support platforms. However, a decision of this magnitude cannot be made without a clear understanding of the V/STOL and ship motion interface and reasonable seakeeping criteria.

Having stated the methodology, its application to V/STOL development may be obvious. The author assumes that the V/STOL structural weight required to withstand the impact of landing on a pitching and heaving ship is a significant design consideration. Equally important is the ability of the pilot to observe and compensate for deck motion during landing and take-off evolutions. If V/STOL operation on smaller ships (e.g., displacement less than 10,000 tons) is contemplated, these motion considerations could become very important. This places a burden on the V/STOL community to adequately define platform motion criteria to support V/STOL operations.

The methodology described above therefore becomes useful in two applications.

First, it can help to make V/STOL managers aware of the operational implications of platform motion on V/STOL effectiveness. Furthermore, it can explain what is reasonable and possible in establishing ship motion criteria.

Secondly, it can alert the ship design community of significant advantages to be gained by a stable platform. This may, in turn, shape the surface Navy of the future.

We must close with a sobering thought. If the V/STOL community is successful in making ship motion a real design consideration, they will be the first developers of a modern naval weapons system to do so. If they fail in this attempt, the Navy may not realize the full potential of V/STOL without a lengthy and expensive learning process that will last many years after V/STOL has entered the fleet.

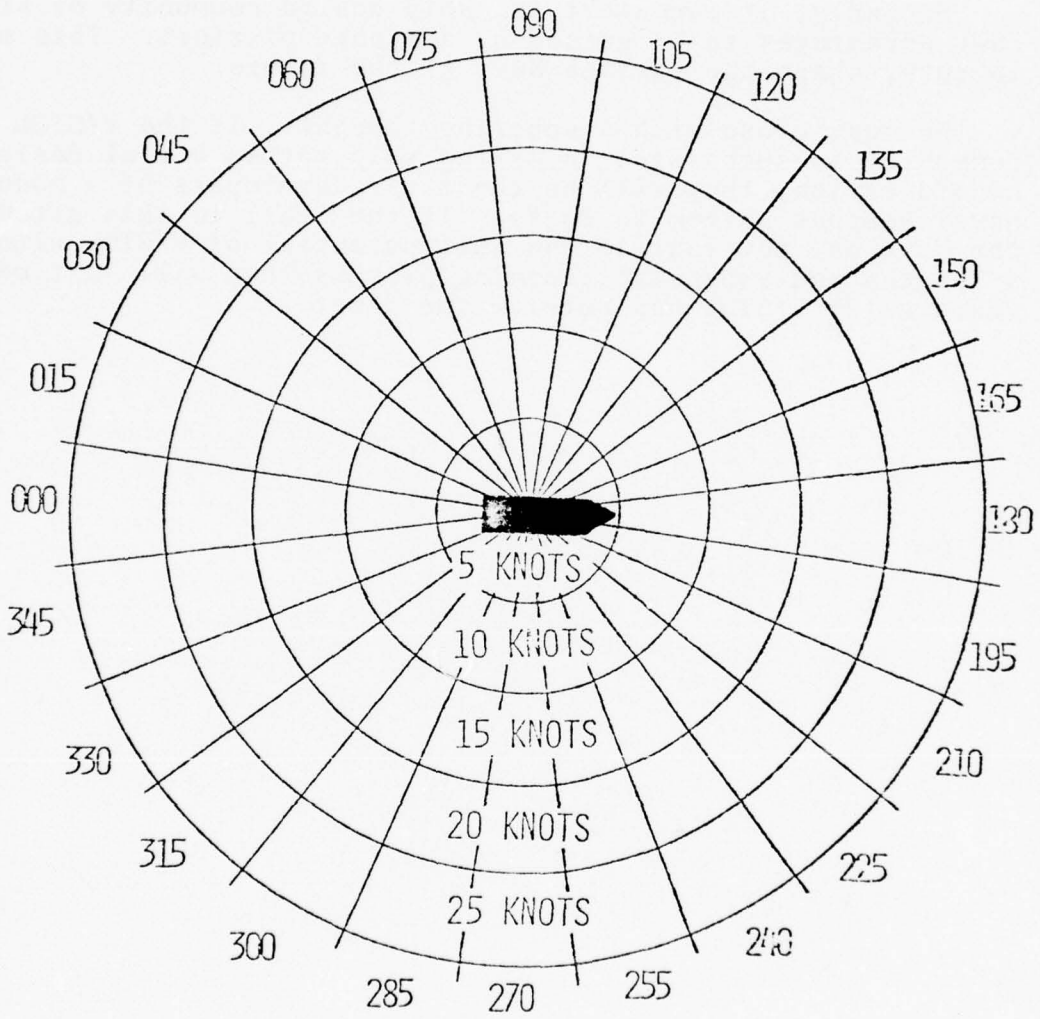


FIG. 1: THE SEAKEEPING MATRIX

TABLE I
PROGRAM OUTPUT EXAMPLE

LIMITING FACTORS FFG 7 ALL SEAKEEPING CRITERIA
(1 - 10)
13.0 SECOND MODAL WAVE PERIOD

SHIP SPEED (KNOTS)	FOLLOWING SEA						BEAM SEA						HEAD SEA
	0	15	30	45	60	75	90	105	120	135	150	165	180
5	8	8	7	7	7	7	7	7	7	7	7	7	8
10	8	8	8	7	7	7	7	7	7	7	7	8	8
15	8	8	8	7	7	7	7	7	7	7	8	10	10
20	8	8	8	8	7	7	7	7	3	3	3	10	10
25	8	8	8	8	7	7	7	3	3	3	3	3	10

LIMITING SEAKEEPING FACTORS

0 NO SEAKEEPING THRESHOLD EXCEEDED FOR WAVES WITH SIGNIFICANT HEIGHTS UP TO 32.0 FEET

1 12.0 DEGREE SINGLE AMPLITUDE AVERAGE ROLL

2 3.0 DEGREE SINGLE AMPLITUDE AVERAGE PITCH

3 MOTION SICKNESS INDICATOR
(20 PERCENT OF LABORATORY SUBJECTS EXPERIENCE EMESIS WITHIN 2 HOURS)

4 BOTTOM PLATE DAMAGE

5 3 SLAMS IN 100 MOTION CYCLES

6 ONE DECK WETNESS EVERY TWO MINUTES

7 12.8 DEGREE DOUBLE AMPLITUDE SIGNIFICANT ROLL

8 6.0 DEGREE DOUBLE AMPLITUDE SIGNIFICANT PITCH

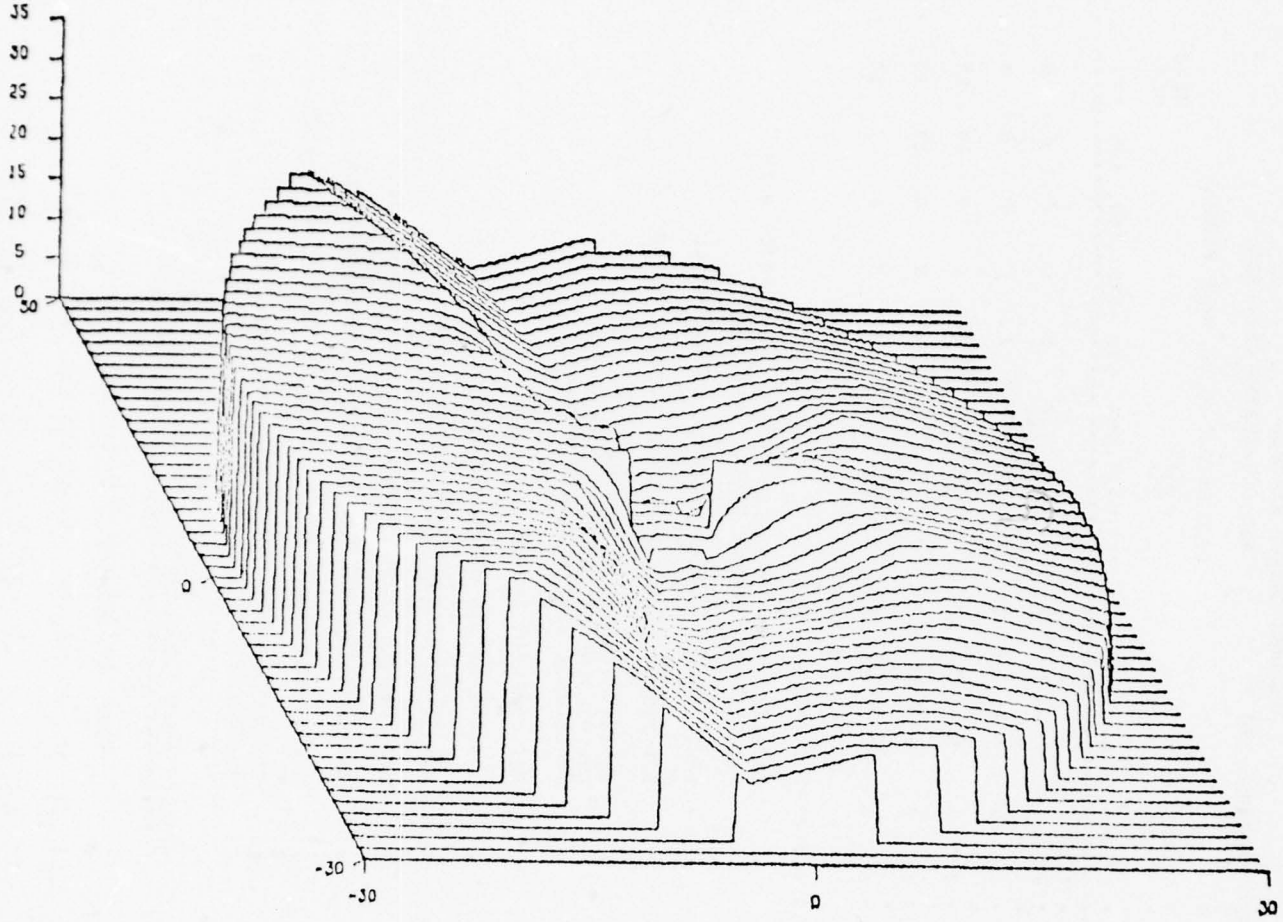
9 7.0 FT/SEC SIG VERTICAL VELOCITY AT THE HELO DECK

10 SONAR DOME EMERGENCE CRITERION
(3/5 DETECTION OPPORTUNITIES)

ACCEPTABLE SIGNIFICANT WAVE HEIGHT (FEET)

SHIP HEADING ANGLE IN DEGREES

SHIP SPEED (KNOTS)	0	15	30	45	60	75	90	105	120	135	150	165	180
5	19	19	12	7	6	6	7	7	7	7	9	15	16
10	20	20	20	12	7	7	8	8	8	9	12	15	15
15	21	21	21	20	10	7	10	10	11	13	15	13	13
20	22	22	23	23	14	7	10	11	12	13	13	12	12
25	23	23	24	25	16	7	11	11	10	10	10	10	11



FFG 7 ALL SEAKEEPING CRITERIA (1 ~ 10) (13 SECWAVE PERIOD)

FIG. 2: SEAKEEPING CONTOUR EXAMPLE

TABLE 2
EXAMPLE OF SEAKEEPING BOX SCORES

FFG 7 BOX SCORES

		NORTH ATLANTIC	
		SUMMER	WINTER
GENERAL CRITERIA ONLY	(1 - 5)	0.95	0.82
GENERAL AND HELICOPTER CRITERIA	(1 - 9)	0.83	0.61
GENERAL AND DOME EMERGENCE CRITERIA	(1 - 6, 10)	0.95	0.81
ALL SEAKEEPING CRITERIA	(1 - 10)	0.83	0.61
5 KNOTS		0.77	0.49
10 KNOTS		0.82	0.59
15 KNOTS		0.87	0.67
20 KNOTS		0.87	0.66
25 KNOTS		0.84	0.62

TABLE 3– CONSTANTS FOR SINGLE-AMPLITUDE STATISTICS

SINGLE AMPLITUDE STATISTICS

Root mean square amplitude, rms	1.00 σ
Average amplitude	1.25 σ
Average of highest 1/3 amplitudes, significant	2.00 σ
Highest expected amplitude in 10 successive amplitudes	2.15 σ
Average of highest 1/10 amplitudes	2.55 σ
Highest expected amplitude in 30 successive amplitudes	2.61 σ
Highest expected amplitude in 50 successive amplitudes	2.80 σ
Highest expected amplitude in 100 successive amplitudes	3.03 σ
Highest expected amplitude in 200 successive amplitudes	3.25 σ
Highest expected amplitude in 1000 successive amplitudes	3.72 σ

DEFINITIONS

σ^2 = Statistical variance of time history

N = Number of successive amplitudes

CONSTANT = $\sqrt{2}\,(\ell n\ N)^{1/2}$, where CONSTANT relates σ to the highest expected amplitude in N successive amplitudes.

NOTES:

1. The highest expected amplitude in N amplitudes is the most probable extreme value in N amplitudes. This value may be exceeded 63 percent of the time.
2. To obtain wave height or double amplitude statistics from rms values, multiply single amplitude constants by 2.0.

TABLE 4

SELECTED SEAKEEPING CRITERIA

GENERAL CRITERIA

1 12.0 DEGREE SINGLE AMPLITUDE AVERAGE ROLL
2 3.0 DEGREE SINGLE AMPLITUDE AVERAGE PITCH
3 MOTION SICKNESS INDICATOR (20 PERCENT OF LABORATORY SUBJECTS EXPERIENCE EMESIS WITHIN 2 HRS)
4 BOTTOM PLATE DAMAGE
5 3 SLAMS IN 100 MOTION CYCLES
6 ONE DECK WETNESS EVERY TWO MINUTES

HELICOPTER OPERATING CRITERIA

7 12.8 DEGREE DOUBLE AMPLITUDE SIGNIFICANT ROLL
8 6.0 DEGREE DOUBLE AMPLITUDE SIGNIFICANT PITCH
9 7.0 FT/SEC VERTICAL VELOCITY AT THE FLIGHT DECK

HULL MOUNTED SONAR CRITERION

10 SONAR DOME EMERGENCE CRITERION (3/5 DETECTION OPPORTUNITIES)

ADDITIONAL GENERAL CRITERIA FOR SWATH

11 18 FT AVERAGE OF 1/10TH GREATEST RELATIVE DISPLACEMENTS AT THE BOW
12 12.8 FT SIGNIFICANT RELATIVE MOTION AT THE PROPELLER

TABLE 5

SEAKEEPING BOX SCORES FOR NAVAL COMBATANTS
OPERATING IN THE NORTH ATLANTIC

	DD-963		FFG-7		FF-1052		CG-26*		3400 ton SWATH Frigate**	
	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
General criteria only (1 - 6)	0.97	0.88	0.95	0.82	0.95	0.81	0.97(1)	0.88(1)	0.99(3)	0.92(3)
General and NSRDC helicopter criteria (1 - 9)	0.93	0.74	0.83	0.61	0.85	0.62	0.90(2)	0.71(2)	0.97(4)	0.83(4)
General and Dome Emergence criteria (1 - 6, 10)	0.97	0.87	0.95	0.81	0.94	0.80	--	--	N/A	N/A
All seakeeping criteria (1 - 10)	0.93	0.73	0.83	0.61	0.85	0.61	--	--	0.97(4)	0.83(4)
5 knots	0.92	0.71	0.77	0.49	0.82	0.54	0.88(2)	0.63(2)	0.95(4)	0.77(4)
10 knots	0.92	0.71	0.82	0.59	0.84	0.60	0.89(2)	0.68(2)	0.96(4)	0.79(4)
15 knots	0.94	0.76	0.87	0.67	0.87	0.65	0.92(2)	0.75(2)	0.97(4)	0.83(4)
20 knots	0.93	0.74	0.87	0.66	0.87	0.64	0.93(2)	0.76(2)	0.98(4)	0.88(4)
25 knots	0.92	0.73	0.84	0.62	0.84	0.62	0.91(2)	0.74(2)	0.97(4)	0.87(4)

*Ship motion data to evaluate criteria 4, 5, and 6 were not available for the CG-26 class

(1) Criteria 1-3 only

(2) Criteria 1-3 and 7-9 only

**Seakeeping criteria modified for SWATH
(3) Criteria (1-3, 11, 12)
(4) Criteria (1-3, 7-9, 11, 12)

DISCUSSION

LTCOL Iles: Have you looked at the damage control potential for a SWATH type of ship? It would appear that this type of ship could take some torpedo hits which a mono-hull couldn't handle and still retain control. Does that make sense or not?

LCDR Steven Olson: It depends on the compartmentation of the struts. Although I'm not a SWATH salesman, that situation has been considered, and you could take a hit in a SWATH and even if you were to lose all your flotation in the whole strut, which isn't likely because you're compartmented, you wouldn't sink. You would probably settle down to the box and the box would float. Mono-hulls today are not compartmentized very much either, and many have all the engineering spaces in one compartment. I don't think that concern has been a driving one, no sir.

LTCOL Iles: It looks like it should be since the submarines are your biggest problem.

LCDR Olson: On the other hand, this particular ship will go faster in a seaway, and that's good for the ASW role. We could get into a very technical discussion about the SWATH, but I'd just as soon avoid that if I could.

Irving Ashkenas: I just wanted to call your attention, if you're not aware of it, that some data on motion sickness has recently been generated in connection with the SESPO. There has been quite a bit of recent work, and it should be good data.

LCDR Olson: It tells you a great deal about when a guy vomits, but not a lot about why. The data I mentioned in my paper was obtained from the SESPO as you had remarked.

Ashkenas: Although you brought up motion as being a critical factor for VTOL, today we heard that really it was the wind that was bothersome. Consequently you're going to have to look at ships from that viewpoint as well as the motion viewpoint. That means that you have to obtain a lot of data before you can do a well thought out design and make all your tradeoff studies.

LCDR Olson: I'm not saying this is the whole problem, just part of it. The main point that I was trying to make was that if you considered ship motion when designing a V/STOL, you would be the first technical community to design a major weapons system for a Naval ship that had considered seakeeping in the last twenty years.

REQUIREMENTS FOR VLA SYSTEMS

CDR Noel S. Flynn, USN

NAVAL AIR SYSTEMS COMMAND
SHIP INSTALLATION DEPARTMENT
LAUNCH/RECOVERY BRANCH

INTRODUCTION

Approach and landing operations present a demanding task to the pilot, particularly in adverse weather and/or shipboard situations. Piloting cue information is of paramount importance for visual flight especially under marginal weather conditions. Present Navy/Marine Corps aircraft operations cover a broad spectrum of unique operational problems involving shipboard environments. The utilization of aircraft aboard both aviation ships and aviation capable ships is being influenced greatly by the advent of vertical or short takeoff and landing (V/STOL) airplanes. The projected missions of V/STOL aircraft will require all-weather operations from various types of ships.

An area of importance in the V/STOL aircraft-shipboard site interface situation is the effectiveness of the visual landing aid (VLA) systems to visually assist the pilot during the approach and landing flight phase. As aircraft and system technologies advance and operational requirements grow, the suitability of existing VLA systems must be re-evaluated and new systems developed to satisfy any deficiencies in existing systems. Assessment of VLA requirements must address current and known future operational situations, including the types of aircraft and the intended landing sites. The direct application of VLA systems which have evolved during the development of conventional fixed-wing facilities is not generally considered acceptable because of the inherent differences between the conventional aircraft and the V/STOL aircraft. However, current VLA systems and technologies can be utilized as a baseline in evaluating requirements.

REQUIREMENTS

The weather at sea is such that final approaches aboard ship are made predominantly utilizing available VLAs. The pilot of an aircraft would most likely use such visual means as are at his disposal for most of their approaches, augmented by, or structured around the instrument approach facilities and procedures that are provided in anticipation of the time when they would be required. The basic problem simply stated is to be able to recover a V/STOL aircraft from an area within the landing zone to a predesignated retrieval site, in this case aboard a ship. The process in achieving this requirement is fundamentally the

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same regardless of type of V/STOL design in that there are certain information criteria required by the pilot in order for him to guide his aircraft through three distinct phases of the recovery (see figure 1).

The progress from any location to the marshal position (a point in space relative to the ship), flight within the holding pattern, and the initial approach can be accomplished utilizing internal flight instruments. The requirement for flight control information, i.e., altitude, speed, drift, closure rate, etc., although necessary, is not critical in regards to the time in meeting the immediate needs of the pilot during the initial segments of the recovery operation. To reach the marshal area the pilot could use TACAN, RADAR, inertial guidance systems, flight instruments. By correctly interpreting the available readouts, the pilot will be able to position his aircraft at a predetermined location, at a desired height, heading in a certain direction, at a specific time. Even with a loss of a certain number of navigational aids either during EMCON (radio silence) or due to mechanical/electrical failure, the pilot could still bring the aircraft to the marshal area and initial approach with only the flight instruments, i.e., compass, time clock, altimeter, airspeed indicator, and inertial navigation.

The descent from the marshal area enters the next phase of the recovery. As the aircraft transcends the predetermined flight path towards the recovery area, new requirements for information are introduced. In addition to the type of information required in the marshal phase, the pilot is now concerned with the rate and change of his altitude, speed, drift, closure rate, etc. The concern for the timeliness of the information becomes more acute than the initial phase of the approach/landing sequence. The pilot however has numerous aids available to him to derive the information required and enough time in space to adjust and correct trends to achieve an optimum descend phase.

Therefore, these first two phases of the approach do not require external visual landing aids and should not be a problem area in future design of V/STOL aircraft due to the type of information required by the pilot versus the means available in deriving the information and the amount of time permitted to make any necessary glide slope adjustments.

It is during the final transition and landing phase where the site facilities become the primary source of information for aircraft control and the requirement for timeliness in obtaining information becomes critical.

For normal operations in the final phase, the aircraft is in the visual recovery mode (VFR) with the pilot relying primarily on the available visual landing aids. The instrument recovery mode (IFR) is used whenever conditions such as weather or darkness dictate. During IFR, the pilot will rely on the internal instruments and voice communications with visual landing aids augmenting the final approach and landing. The worst case condition for the pilot in retrieving his aircraft is during a radio silence (EMCON) IFR night. Under this condition, the pilot must

SHIP LANDING PATTERN, IDEAL AND INFORMATION REQUIREMENTS

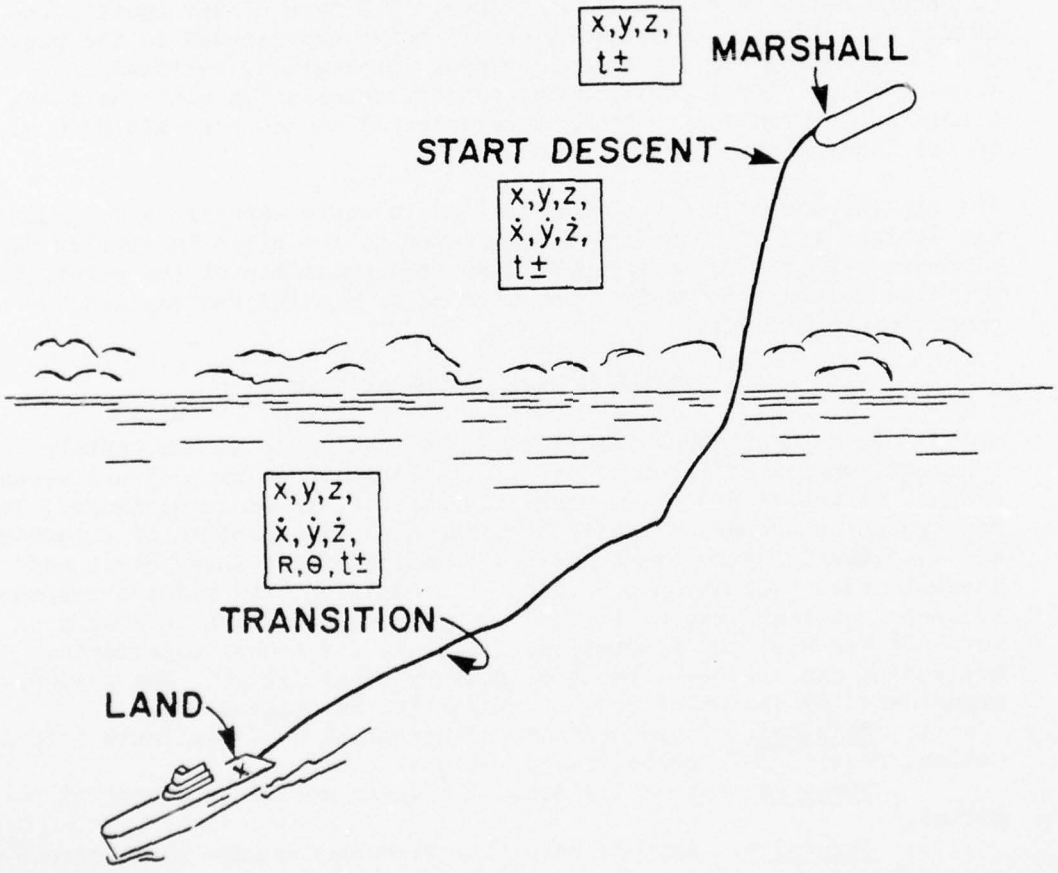


Figure 1

rely totally upon the external visual aids and the internal instrumentation for executing the transition and landing. Communications are not passed between the ship and aircraft during EMCON and there is no visible horizon on an IFR night. Every element of the visual scene must therefore be correlated into a meaningful, mutually supportive, source of data for the pilot in order to make rapid and valid decisions. The pilot controls adjustments to flight direction, altitude and airspeed necessary to maintain the desired flight path and speed relative to the terminal site.

The final approach for the pilot is the transition from flight instruments to visual site references and it is during this time when it is most important to know the exact position of the aircraft and any rate of change relative to the landing area. The type of information required pertains to the tracking errors being experienced in the position of the aircraft, e.g., vertical descent information, vertical/longitudinal/lateral position and rate of translation with the timeliness of information becoming more critical as the aircraft gets closer to the landing site.

The final phase of the V/STOL operation is where aircraft and landing aid designs are of significant importance to the pilot in retrieving the aircraft safely. To better understand the situation of the pilot, it would be helpful to consider the sources of his information and how he controls the aircraft.

PILOT SOURCE OF INFORMATION

The pilot, as most other individuals, has available to him certain inherent sources of information. Included in these sources are visual senses, cutaneous senses (touch), kinesthetic senses (arm, finger, leg, etc. position awareness), orientation senses (integration of cutaneous and kinesthetic senses with balance function of the inner ear), and instantaneous evaluation of events. In addition, the pilot's response to certain stimuli may be influenced by intuition which generally reflects aeronautical adaptation, training, alertness, experience, motivation and the development of sensory capabilities. The responses experienced by the pilot can be categorized as follows:

1. Reasoned. Consideration and correlation of available information, resulting in premeditated actions.
2. Directed. Signalled direction which defines a course of action.
3. Intuitive. Actions resulting without recourse to inference or reasoning.
    a. Conditioned response - result of experience, indoctrination, training and practice.
    b. Anxiety response - reflecting a self-preservation drive.

Visual sensibility becomes a complex process because many task elements and the multitude of information sources are synergistic in their effects. Utilizing the visual senses in flying an aircraft, the following processes are used:

Alignment - Sighting, obscuration and masking, parallox interpretation

Ranging (Distance and altitude) - Instantaneous comparison of exterior objects, time-span comparison, depth perception

Speed - Changes in ranging information, direct estimation.

Drift - Horizontal/vertical displacement from a reference datum line.

PILOT'S CONTROL OF THE AIRCRAFT

The pilot generally utilizes the following to control the aircraft whenever visual landing aids are not provided:

Altitude Control -
1. Appearance of the horizon related to structural elements in the aircraft
2. gyro-horizon instrument
3. altimeter
4. rate of climb indicator
5. airspeed indicator
6. power required to maintain speed.

Directional Control -
1. Known points on the earth's surface and apparent progress with relation to them
2. gyro-stabilized compass or repeater
3. wing position on the gyro horizon
4. turn-rate indicator
5. slip indicator.

Airspeed Control -
1. adjustment of power
2. adjustment of attitude controls
3. interrelating the information sources.

Two items of importance in considering the final vertical descent of the V/STOL aircraft are (1) Ideally, the landing area should always be within the pilot's view and (2) any alignment and stopping point should be attainable with a minimum amount of aircraft maneuvering.

Proper execution of a shipboard approach/recovery is a demanding task and is an extensive addition to pilot work load. Such variants as ship's speed, drift angle, wind over the deck, and relative motion between the aircraft and the ship must be considered in recovering the aircraft safely. It is here that the visual landing aids (VLA) should complement the design of the aircraft.

VLA DESIGN CRITERIA

In establishing design criteria for VLA systems, the following requirements should be observed:

1. Satisfaction of mission performance criteria
2. Safety of Flight
3. The expansion of current envelopes of safe operation.

Secondly, there is a criterion which is inherently a part of the foregoing, but deserves separate mention because of the need to constantly observe its impact and to occupy a position as a line item in test and evaluation documents. This criterion is satisfactory pilot work load. Work load is construed to include the concern for all human factors at the man-machine interface which affects a pilot's task involvements.

Visual landing aids should be designed to provide full information to V/STOL landing sites. Their objective is as much to stand as visual barriers to collision with water, ground, superstructure or appurtenances as it is to provide approach and landing guidance. While the aircraft is relatively far from the site, requisite information may be minimal, but as the distance is closed, the need for precision increases. The VLA presentations should provide immediate intelligence for three dimensional positioning trends and rates thereof, approach path, closure rate, landing area orientation, relative wind, deck status, ship motion, and as many additional elements of information as may be required for obstruction clearance, deck spotting and other items of interest. A review of the operation of the AV-8A and the role of the VLAs in attempting to overcome aircraft deficiencies highlights the need for close cooperation between aircraft designers and VLA designers in order to obtain the optimum aircraft-shipboard interface.

AV-8A FLIGHT CHARACTERISTICS

In wingborne flight, the aircraft exhibits handling qualities similar to conventional aircraft. Flight control is achieved by the use of ailerons, slab elevators, and a rudder. A considerable change in flight characteristics is experienced during hover or in the low speed regime. During this time, the control is achieved by vectoring adjustable propulsion forces from the normally aft jet configuration to a downward thrust of the jet forces. Currently, the AV-8A aircraft utilizing this procedure in the jet-hover regime is neutrally stable in pitch and roll and is unstable in yaw at low airspeeds. The intake momentum drag is the destabilizing force which affects the aircraft considerably below 50 knots. An appreciable yaw between 30 and 90 knots can lead to loss of lateral control. Rolling moments produced by yaw are proportional to the product of indicated airspeed, angle of attack and sideslip angle. Additional instability is created in the final approach to the landing by the jet fountains produced by the downward thrust of the jet engines, surface irregularities and wind gusts. A minimum hover height of 25 feet is dictated by the exhaust velocity at ground level which can achieve 300-400 knots at 4 psi. If this pressure is permitted to build up under a surface, the lifting force becomes tremendous and can lift an 8 inch steel plate. At low hover heights,

the aircraft also becomes susceptable to foreign object damage and exhaust gas ingestion.

AV-8A VISIBILITY

The AV-8A is capable of day VFR operations provided some basic visual landing aids are provided. However, operations cannot be classified as ideal since the pilot cannot view the landing area during the final approach, the hover, and the vertical descent to touchdown. The problems inherent in day VFR operations are severely compounded by night conditions. The pilot must be afforded glide slope information to execute a decelerating transition approach to the ship.

The visibility from the cockpit allows the pilot a clear view of the landing area during the initial phase of the decelerating transition. As the aircraft nears the termination of approach, the landing area becomes totally obscured from the pilot's view. An AV-8A visibility profile from the pilot's seat is presented in figure 2. A hovering position gives a fuselage attitude of about 7½ degrees, i.e., the nosewheel is slightly higher than the main wheels. This configuration restricts the pilot's forward view to a maximum downward visibility of 12 degrees.

AV-8A SHIPBOARD FLIGHT LIMITATIONS

In addition to inherent aircraft characteristics, additional operating limits are imposed for shipboard operation. A maximum permissible crosswind of 10 knots for day recoveries and 5 knots for night recoveries is allowed for operation aboard an LPH class ship. The maximum wind-over-the-deck is 40 knots and vertical operations are not conducted with a tailwind component. In regards to ship motion, the operational situation will determine the actual limiting values. Present operations suggest that vertical landings be performed with caution whenever the roll motion is greater than ± 3 degrees and the pitch motion is greater than ± 1 degree.

SHIPBOARD VERTICAL LANDING/APPROACH

The present V/STOL shipboard landing approach procedures are quite similar to conventional carrier-based aircraft procedures, except for the final phase of the flight. The V/STOL approach maneuver commences in level flight at 12 nautical miles and continues in conventional flight until reaching a point 3 nautical miles astern, at which point the (AV-8A) engine nozzles are positioned to 40 degrees. Once intercepting the glide slope, the engine nozzles are positioned to the hover

AV-8A COCKPIT FIELD OF VIEW

BINOCULAR VIEW - FIXED HEAD POSITION - NORMAL SEATING POSITION

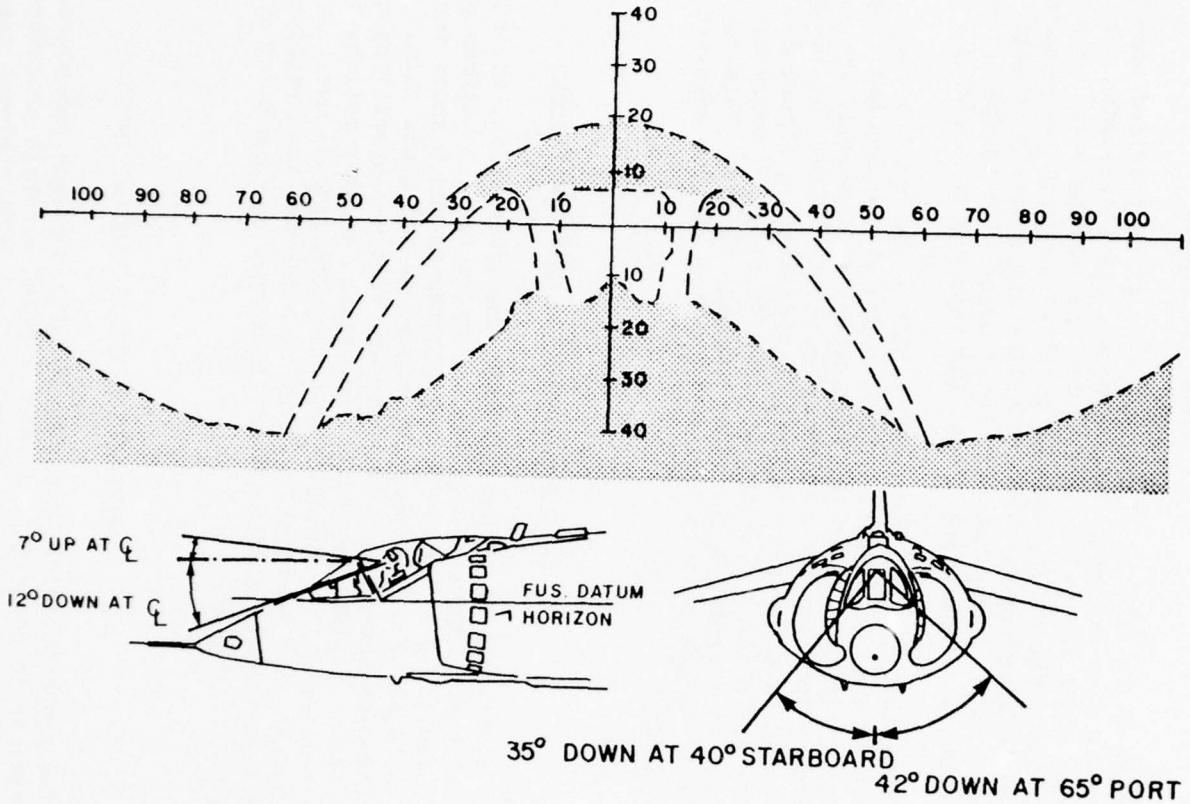


Figure 2

stop and a descent along the glidepath is initiated. When within a few hundred yards astern of the ship, the aircraft is turned and departs from an approach along the extension of the flight deck centerline. The approach is completed by flying a track off the port side of the ship to a hover point abeam the landing spot and then translating laterally and descending to the desired touchdown point (see figure 3). This procedure provides good visibility of the ship throughout the approach, avoids flight over the stern deck area and affords a straight ahead waveoff route. The approach is normally terminated at 50 to 60 foot stabilized hover, followed by a vertical descent to the landing area.

VISUAL LANDING AIDS

In order to alleviate some of the difficulties experienced in the final phase of landing, the following VLAs were made available to the AV-8A aboard the interim sea control ship USS Guam during the trials at sea.

- Painted Deck Centerline (Aircraft lineup)
- Stabilized Glide Slope Indicator (Glide Path)
- Centerline Lighting and Fantail Drop Lights (Lineup)
- Floodlights and Deck Edge Lights (Depth perception)
- Green "Cut" Lights (EMCON or lost communications)
- Red "Wave-off" Lights (LSO wave-off calls)
- Landing Position Indicator (Determine fore and aft positions relative to the landing spot)
- Fixed Horizon Bar and a Stabilized Horizon Bar (Horizon reference and ship motion information)
- Rotary Becon Lights (Homing).

Subsequent to the USS Guam trials, air operations with the AV-8As have been accomplished aboard an aircraft carrier. In addition to the aforementioned VLAs, the V/STOL pilots had the opportunity to evaluate the Fresnel Lens Optical Landing System (FLOLS) as a visual landing aid to assist the V/STOL aircraft in its approach through the jet hover transition.

In general, the visual landing aids provided the V/STOL pilots were beneficial. The VLAs were fairly simple and in certain cases self explanatory. Those requiring additional explanations are discussed below along with the suitability for V/STOL operations as expressed by the pilots.

Glide Slope Indicator. The single cell fresnel lens tri-color glide slope indicator was employed aboard the ship to provide height control cues during the approach. The glide slope indicator (GSI) was positioned on the island structure some distance above the deck level. The GSI was stabilized in pitch and roll for effective shipboard utilization. The GSI unit produced a glide slope of 2½ degrees at the intersection of the amber/red sectors and the red beam was visible down to the water. The amber ("on") beam produced a 1/2 degree vertical coverage and the green ("high") allowed for reasonable excursion of the aircraft above the command path.

VSTOL LANDING PATTERN

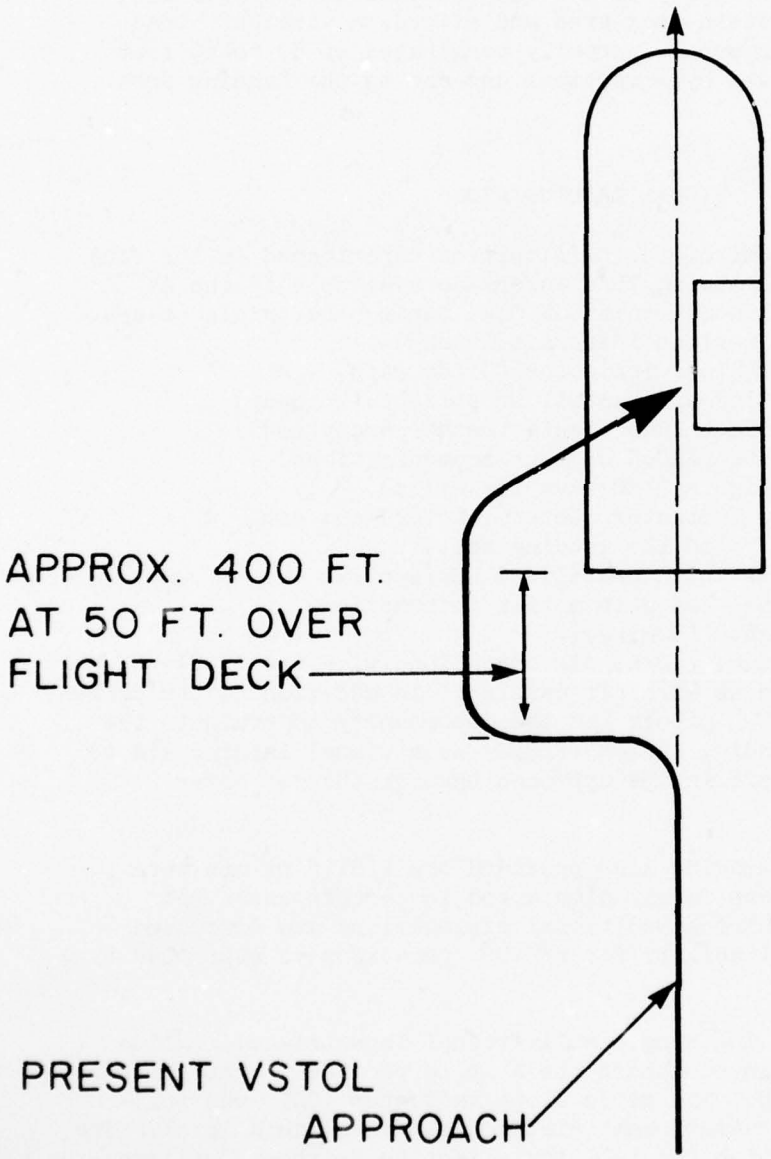


Figure 3

Information submitted by the pilots indicated that although the system was better than nothing, it was unacceptable due to lack of trend information and poor intensity which prevented quick acquisition along the glide slope path.

Landing Position Indicator. The intent of the landing position indicator (LPI) was to provide the pilot visual cue information relating to the longitudinal position of the aircraft in reference to a desired landing point. The device employed a single-cell fresnel lens glide slope indicator similar to the GSI mounted on its side and directed toward the landing spot from its location on the island structure. The color observed by the pilot was dependent upon his longitudinal position along the deck centerline.

The information obtained indicated that the device was not used. Specific observations were that the LPI was out of the pilot's primary field of view when the aircraft was in a position where the information was most pertinent.

Horizon Bars. Two horizon bars were employed, both facing aft to provide cues to the pilot during an approach. One bar was located on the island structure near the GSI and stabilized to negate ship roll to provide a reference of true horizon. The second bar was affixed to the stern of the ship to provide a reference for ship motion.

The stabilized bar was not an effective cue device as it was inferior to any natural horizon and to the HUD display. Additionally, its relatively small size for distant viewing and its location outside the pilot's primary field of view detracted from its effectiveness. The horizon bar on the stern provided useful information but the threshold lights provided the same information and were preferred to the bar which was positioned off the stern of the ship.

Fresnel Lens Optical Landing System. The Fresnel lens optical landing system (FLOLS) consists of two groups of green datum lights, in a horizontal line, with an optical system (lens box) in the center which produces a bar shaped virtual image ("meatball") 150 feet behind (with respect to the approaching pilot) the datum lights. The lens box consists of five individual lens cells positioned in a vertical line one on top of the other. Lights located directly behind each lens of the cells produce the virtual image. The top four cells have yellow filters and the bottom cell has a red filter. The system operates on a relationship between the image and the horizontal rows of green datum lights. The virtual image and pitch axis of the lens box form a plane (datum plane). Intersection of this plane and the vertical plane through the centerline of the landing runway is the proper glide slope for the eye of the pilot. The image is visible to the pilot within a vertical range of plus or minus 3/4 of a degree from the prescribed glide slope. The horizontal spread of the image about the optical axis of the lens box is 20 degrees to either side. A computer system utilizing ship motion data from the ship's gyro keeps the optical axis of the lens box stabilized

to a point in space during ship's pitch and roll motion. Comments obtained from the V/STOL pilots indicated that the FLOLS was providing the type of information required to assist the pilot in obtaining the desired attitude while transitioning from wing borne to jet hover flight. This information was useful from about 1½ miles on final until the aircraft obtained hover configuration at about 400 feet aft and 50 feet above the flight deck, at which time the landing pattern deviated from the straight in approach. With the exception of the relatively short range of the FLOLS (1½ miles), the system provided the pilots with the type of information desired. However, the FLOLS is not considered adaptable to smaller aviation capable ships. The FLOLS was designed for deck edge mounting, requires a considerable amount of space and is a very expensive system to be considered for production in the numbers required to outfit the comparatively large number of air capable ships.

Green "Cut" Lights and Red "Wave Off" Lights. A horizontal row of green lights are mounted above the optical lens and are turned on to indicate a "cut" to the pilot when the aircraft is on the touchdown point. To indicate a wave-off, two vertical columns of red lights are simultaneously flashed at approximately 90 flashes per minute. Both sets of lights are operated by a Landing Signal Officer (LSO). A landing signal officer or enlisted is required for all shipboard landing operations of the V/STOL aircraft. His primary function is to observe the final phases of the approach and landing operation and to provide to the pilot additional information for height control. Additionally, the LSO observes the status of the landing area to insure a clear deck for landing.

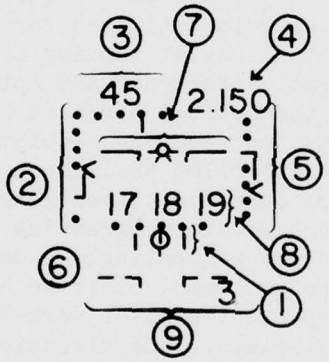
In the AV-8A, a head up display (HUD) is also used as a visual aid in the cockpit by the pilot. The HUD is capable of providing several modes of information to the pilot. The information is projected off of a cathode ray tube and displayed on the center panel of the windshield. This arrangement allows the pilot to still observe in the forward direction while obtaining the information displayed. An AV-8A HUD in the V/STOL mode is shown in figure 4.

V/STOL VLA SOLUTIONS

A practical solution to providing the AV-8A V/STOL aircraft with an optical landing system (OLS) designed for the pilot's needs, was to capitalize on the proven concepts of the FLOLS, improve the acquisition range, reduce the size to be adaptable to small ships and reduce the overall costs in order to afford the maximum number of systems within a reasonable procurement package. The following outlines the requirements and VLA solutions for an AV-8A approach:

AV-8A HEAD UP DISPLAY

VSTOL MODE



1. SIDESLIP BALL & LIMIT REMARKS
2. ANGLE OF ATTACK SCALE
3. GROUND SPEED
4. BAROMETRIC HEIGHT
5. VERTICAL SPEED SCALE
6. AIRCRAFT SYMBOL
7. HORIZON BAR
8. HEADING
9. ELEVATION BAR

Figure 4

Requirement	Solution
Proper Glide Slope (From 3 nm on final)	Vertical Lens System & Horizontal Datum Lens
Rate of Movement through glide slope	Compares meatball with datum lights
Knowledge when becoming dangerously low	Flashing red low cells
Closure rate	Perspective view of entire display
Larger vertical display angle	2^{o} vert angle (vs $1\frac{1}{2}^{o}$ for FLOLS)

A fabricated version of a small FLOLS system has been evaluated aboard the USS Guam (figures 5 and 6). As this system is further developed, it is anticipated that it will meet all of the requirements of the AV-8A V/STOL approach to within 400 ft. aft and 50 ft. above the deck of the ship. Other landing aids being investigated for the recovery of aircraft are: the Hybrid Terminal Assist Landing System (HYTAL) which utilizes a combination of radio frequency and optics in guiding the aircraft for recovery; and the Optical Aircraft Recovery System (OARS) which is a purely optical system requiring equipment aboard the aircraft to recover the aircraft without pilot assistance during EMCON. These systems will be reviewed not only for conventional aircraft but V/STOL aircraft operation. Although we are progressing forward in providing the type of VLAs the pilots are requesting, we do not feel that we have yet all the answers to their problems, or if we ever will have the answers. Our goal is to improve the pilot work load situation by improving the visual aids displays. The situation should be that the aircraft is so designed or configured that the pilot could sustain a certain amount of degradation in VLAs or stabilization and still have an acceptable work load (see figure 7).

SUMMARY

The challenge to provide viable solutions to problems inherent to V/STOL operations is apparent. Considerable improvement in visibility and stability may be achieved by a redesigned aircraft. However, the requirement to provide visual landing aids to the pilot will continue regardless of the design. Visual landing aids are potentially capable of conveying real or virtual information with respect to flight control parameters and navigation. The need to develop visual landing aids tailored specifically to the requirements of the V/STOL aircraft is an absolute necessity if we are to meet proposed operation deployment concepts.

V/STOL LANDING SYSTEM

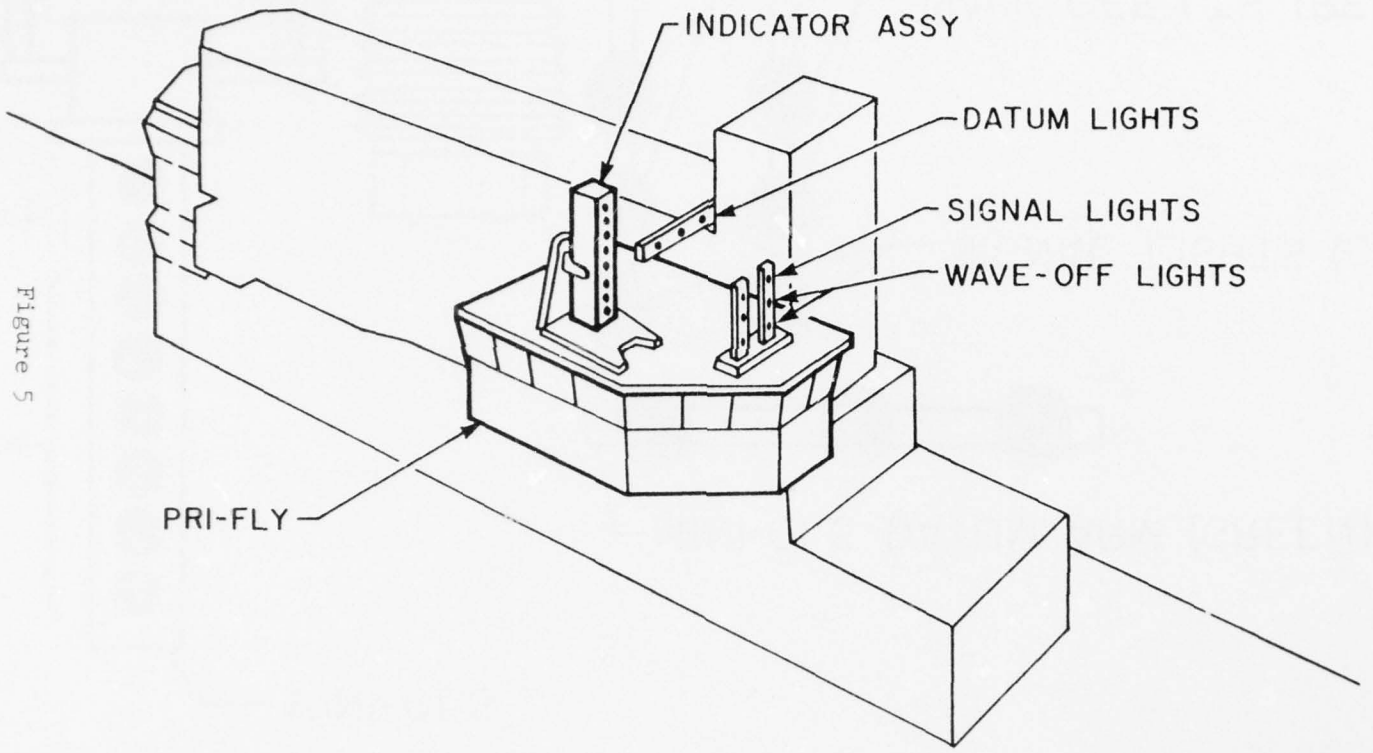
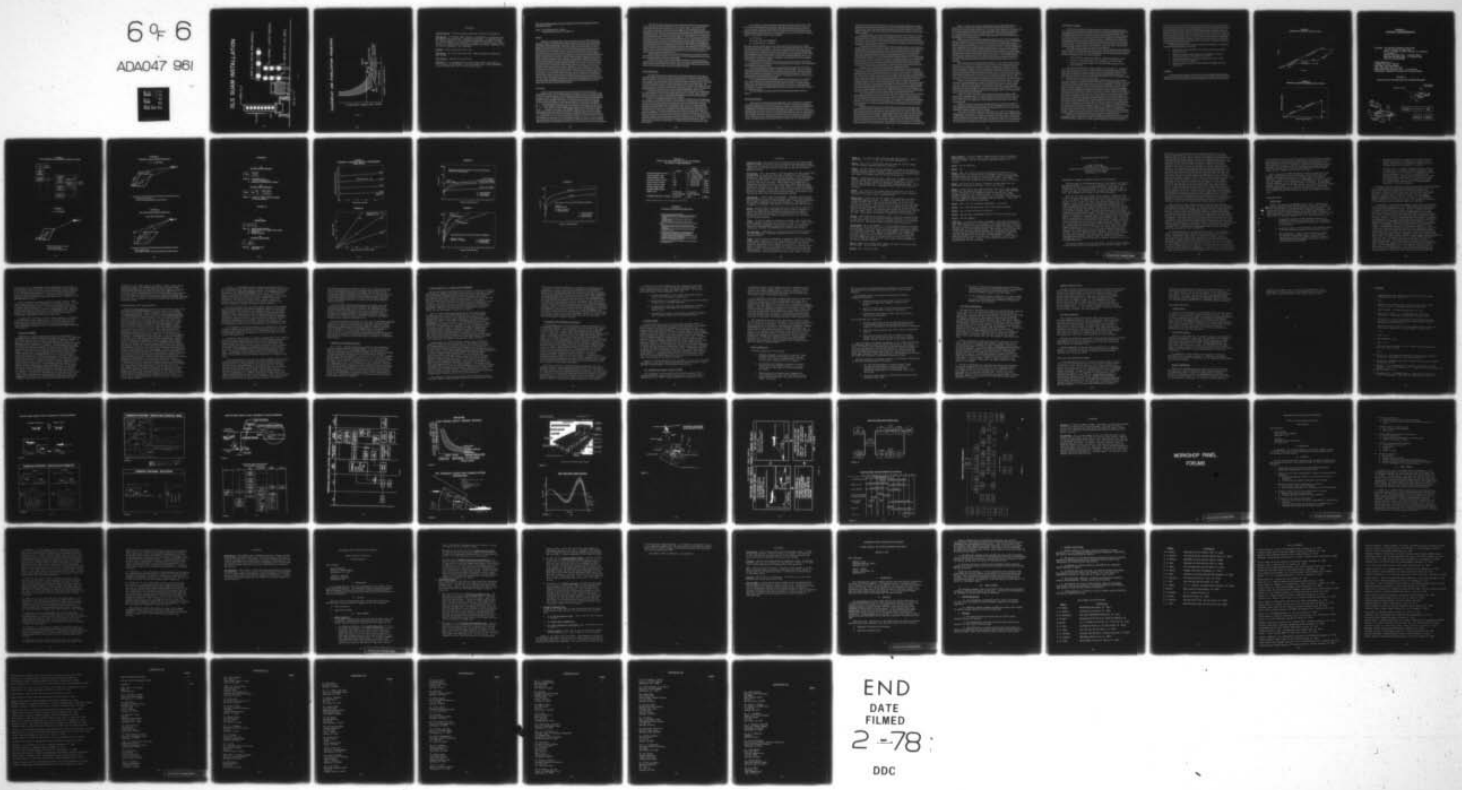


Figure 5

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PROCEEDINGS OF NAVY/NASA VSTOL FLYING QUALITIES WORKSHOP, HELD --ETC(U)
AUG 77 C J MAZZA, D M LAYTON, L V SCHMIDT

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OLS GUAM INSTALLATION

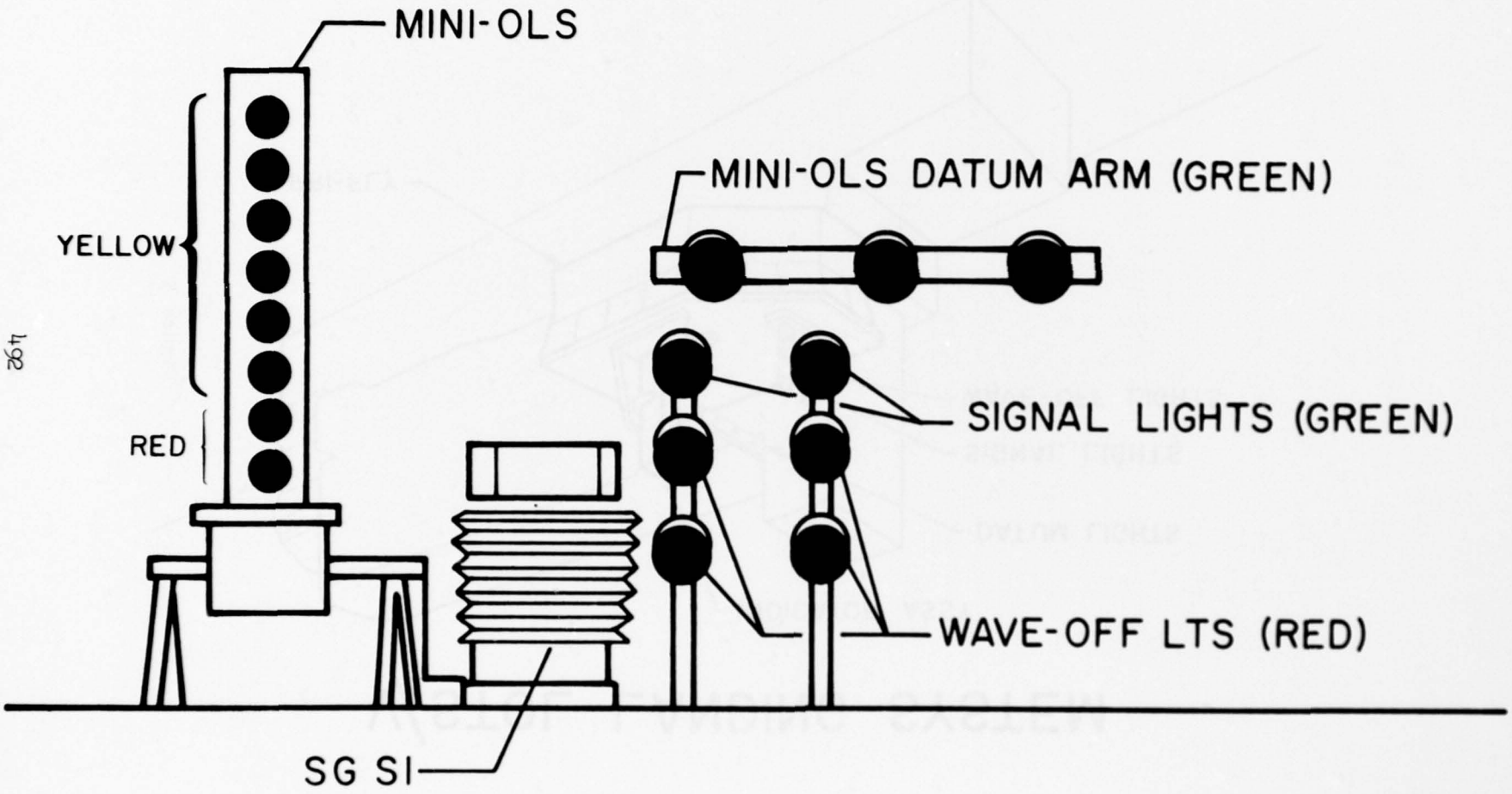


Figure 6

VLA/DISPLAY AND STABILIZATION TRADE-OFFS

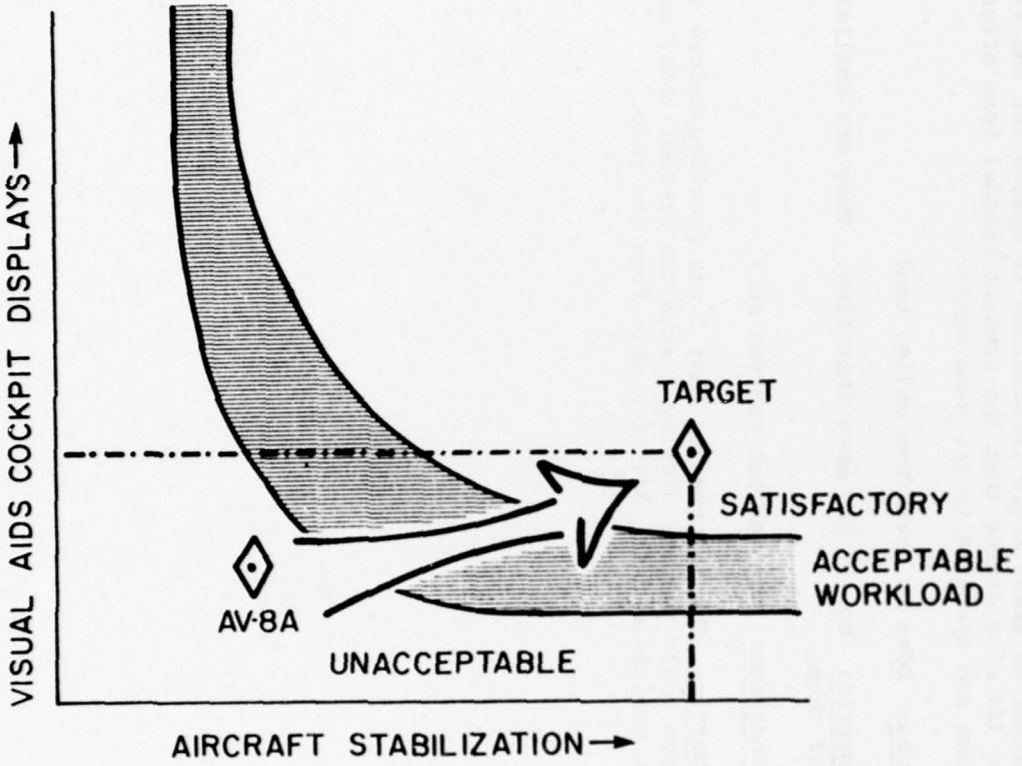


Figure 7

DISCUSSION

Irving Ashkenas: Could you explain again what that Mini OLS system is?

LCDR Norris: It's termed "mini" because it's physically a lot smaller that the Fresnel lens system that I showed you previously. It operates exactly the same but differs in that it presents a wider vertical angle. We feel that wider vertical angle information is needed for the V/STOL pilot instead of the 3/4 of a degree that the present Fresnel lens offers. Basically it's the same and operates in the same manner.

Ashkenas: Does it have five cells, too?

LCDR Norris: No, it has more than five. They are smaller and there are more of them.

Seth Anderson: How far out can you see?

LCDR Norris: The information that I was provided before I came here was that you could see the display. With the Fresnel lens, useful information is not available until 3/4 of a mile from the ship.

VTOL/HELICOPTER APPROACH AND LANDING GUIDANCE SENSORS FOR NAVY SHIP APPLICATIONS

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Abstract

Approach and landing guidance sensors are essential to recover VTOL aircraft and helicopter on ships. The guidance sensor system must provide coverage from approximately five miles to touchdown under clear and adverse weather conditions of heavy rain and zero ceiling/700 feet horizontal visibility. The sensor accuracy must be better than ± 1 foot in position and ±1 foot per second in velocity or rate of change in position during the last few hundred feet before touchdown because of the small moving landing spot and the lack of maneuvering space on non-aviation, aviation ships. The accuracy can be relaxed at greater distances, but is limited by the quality of the approach control during deceleration and descent, and the turbulence/gust environment. There are many alternative techniques which feature different operating frequencies from microwave to optical-infrared, different geometric techniques of position fixing by range and angle measurements from a single point or points on a short baseline available at the landing platform typically forty feet wide. Microwave systems offer the potential of attaining the ceiling/visibility objectives, but must be tested to show its capability of providing the in-close accuracy, especially in a severe multipath environment. Hybrid frequency systems with microwave and electro-optical (E-O) sub-systems can achieve the accuracy, but not the ceiling/visibility objective. Safety and pilot acceptance requires that the microwave to E-O transition be made smoothly, and with sufficient time and distance to allow the pilot to check the final system and decide whether to continue or discontinue the approach. Since Navy operations involve many different terminals, aircrafts and systems for air traffic control, navigation and landing, it is essential that the landing guidance system utilize, or be compatible with existing and planned systems, and be integrated into the Navy and Marine Corps air traffic control and landing systems.

Introduction

Approach and landing guidance sensors are essential to recover VTOL aircraft and helicopter on ships. In low visibility weather, the guidance sensors are required to enable the pilot to initiate the approach, and provide guidance signals to the pilot or autopilot during the approach, hover, landing and wave-off. With the pilots view of the small moving/shipboard platform restricted during the final descent to touchdown because of limited cockpit field of view, the pilot needs guidance information during the final critical phase of the landing. Current Navy landing guidance systems, with the exception of the automatic AN/SPN-42, provide guidance during the approach phase only and impose the requirement for the pilot to land the aircraft, visually. On aviation facility ships, a gunfire control radar has been adapted for use as an approach control radar. The AN/SPN-42 landing system is too large for small aviation facility ships, and it cannot provide the short range coverage and accuracy required for V/STOL aircraft in hovering over or landing on a small deck. Systems under development, such as Marine Remote Area Aircraft Landing System (MRAALS) and the Microwave Landing System (MLS), are satisfactory for the piloted approach phase, but they are not precise enough to provide guidance for hovering over and landing on a small pad on the ship's deck. Moreover, MRAALS or MLS will need additional velocity sensors for an automatic and decelerating approach.

The VTOL aircraft or helicopter pilot has a much more difficult task during approach and landings than the CTOL aircraft pilot. If one examines Figure 1, the altitude versus distance approach profile, the paths flown do not appear to be drastically different, with the exception of the final vertical descent for the VTOL aircraft. The altitude profile does not graphically show the VTOL aircraft decelerations during the approach and the transition from wing lift to powerlift. The difference between VTOL and CTOL approaches is best illustrated by examining the approach on an energy basis (Figure 2). For the CTOL case, the power and flaps have been set and the aircraft must be positioned along a two translational axis by the use of two basic controls. As seen on the diagram, the kinetic energy is kept constant while the potential energy is bled off and then after touchdown the kinetic energy is then dissipated by roll out along the runway or the arresting wire on a Carrier. The VTOL must simultaneously dissipate both the kinetic and potential energy and arrive at the landing spot with relatively zero energy. He must control his motion along three translational axises using three controls. This is the basic reason for the increased difficulty in landing a VTOL versus a CTOL and why it is easier to get into trouble and harder to get out.

Additionally, both the CTOL and the VTOL under wing lift are dynamically stable (if perturbed, the oscillations will damp out). However, the VTOL, during transition and in powerlift, is generally unstable, or at best, neutrally stable.

The need for a sensor system to provide position information through the approach, transition, hover, and landing phases is obvious. What is not quite as obvious is that the requirements for guidance also dictate a system that provide accurate three dimensional velocity information to have a smooth approach control acceptable to the pilot.

General Requirements

The guidance sensor system must provide coverage from approximately five miles to touchdown under clear and adverse weather conditions of heavy rain and zero ceiling/700 feet horizontal visibility. The sensor accuracy must be better than ± 1 foot per second in velocity or rate of change in position during the last few hundred feet before touchdown because of the small moving landing pad and the lack of maneuvering space on small aviation facility ships. The accuracy can be relaxed at greater distances, but is limited by the quality of the approach control during deceleration and descent, and the turbulence/gust environment. Figure 3 summarizes the general operational requirements for the approach and landing guidance position sensor.

The guidance sensors must provide the necessary control information to the pilot and/or the VTOL autopilot to effect a final physical coupling of the two vehicles. Figure 4 illustrates the motions involved. In order to accomplish this coupling, all rotational and translational motions of both vehicles must be sensed and accounted for.

Figure 5 is a simplified illustration of how the flight control function can be performed. The illustration covers both the automatic or pilot aided cases. Rotational motions of the VTOL would be sensed internally using inertial sensors and be part of the control loop. The ships motions can be sensed inertially and the information fed to the control command generator. The ships motion data will be used to compensate for ships motions and to make short term predictions for the final descent to touchdown. The requirements for this prediction are not covered in this paper. The relative translational motion between the ship and the VTOL will require external sensors. It should be noted that there are three translational axis control loops that must be closed, thus the requirement is for relative position (x, y, z) and velocity ($\dot{x}, \dot{y}, \dot{z}$) information. Doppler type range rate measurements can not be resolved into 3-dimensional velocity vectors without being used in conjunction with change of position measurements. Thus, a sensor system that measures or derives the x, y, z position and velocity is required for a VTOL landing system.

Electromagnetic systems are capable of measuring angles, ranges and range rates. There are three basic techniques available to measure ranges and/or angles and compute position in x, y, z coordinates. Each has its own geometric advantages and disadvantages when used for a shipboard approach and landing system. The error caused by noise varies in magnitude for the computed position and velocity data in the coverage sector for each of the three basic techniques. Figures 6, 7 and 8 illustrate the three basic techniques:

(a) R, Θ, ϕ case

(b) $\phi_1, \Theta_1, \Theta_2$ case or triangulation

(c) R_1, R_2, R_3 case or trilateration

The relative locations of these sensors on the VTOL aircraft or the ship can also be reversed from the locations shown on Figures 6, 7 and 8, but the principle remains the same. The coverage of the sensor systems are dependent on such factors as approach profiles, safety, approach procedures and wave-off requirements for the various aircraft types. The coverage of the approach and landing guidance system must begin before the transition from winglift to powerlift. Current Harrier transition begins at approximately 3 nautical miles and 400 feet altitude. For an automatic landing, it is necessary to operate to touchdown. For pilot approach and hover guidance, coverage to near touchdown is required.

The dimensions of the entrance window for the system at the maximum range has not been determined but ± 40° azimuth and 2° to 20° elevation should be adequate to cover approaches from both port and starboard sectors.

The system should also be capable of providing guidance through a waveoff as well as takeoff since the transition from powerlift to winglift is equally complex. It has not been determined whether position updating from the precision position sensor will be absolutely required under poor visibility and/or automatic wave-off, take-off and initial departure. It may be that existing airborne sensor data inputs will be sufficient. This problem must be resolved before the selection of the position sensor system is made.

The meteorological and oceanographic maximums and minimums under which sensor system must function can be derived from operational analysis supplemented with world climatic data. These values can strongly affect the choice of system (i.e., minimum visibility in fog could affect the choice between an electro-optical or a microwave system) and system requirements (i.e., amount of rainfall would directly affect the selection of frequency and power for a microwave system.)

The meteorological values being used in the NAVTOLAND Program are given in Figure 3.

Accuracy Requirements

The accuracy of the approach and landing guidance sensor is dependent on such factors as allowable control/errors, approach profiles, safety, structural and aerodynamic limitations, environmental disturbances, crew comfort and pilot acceptance. The small size of the shipboard landing pad with its attendant obstructions places rather severe three dimensional accuracy requirements on the sensor system near the small ship landing platform. With a 3 to 4 foot allowable touchdown error and a 4 feet per sec vertical touchdown velocity desired, the requirement for relative position and velocity accuracy between the aircraft and the ship has been tentatively set to one foot and one foot per second (1-sigma) noise error in the touchdown and final descent volume. The allowable bias error in position shall be less than 1 foot. The requirements for

position accuracy, three dimensional velocity accuracy, and the related update rates and allowable position and/or velocity time averaging can only be thoroughly substantiated by simulation because of the complex inter-relationships between these values and the dynamics of both the ship and VTOL as well as the meteorological environment (especially wind gusts) and the oceanographic conditions.

Experience gained from current CTOL landing systems and some preliminary outer loop simulation indicates a minimum update rate requirement of 10 per second. Analysis to determine position noise error limits for approach and transition to hover showed that the position and velocity accuracy required were determined primarily by the pilots acceptance limits of linear accelerations, control stick motions and aircraft rotations under flight path error limits, especially during the last 1000 feet before touchdown.

Preliminary outer loop simulations using a helicopter model which has a first order linear transfer function with a 3.3 second time constant, a 0.1 g acceleration limit for pilot acceptance, a 10 HZ position and command update rate and a 2 second maximum interval for computing velocity from successive position samples, indicated that an 8 feet per second forward velocity noise error (1-sigma) was barely acceptable for decelerating approaches in the range sector from 1000 feet to 300 feet. The single sample horizontal position data noise error corresponding to the 8 feet per second velocity error is 11.3 feet since simple averaging over a 2 second interval was used to derive velocity. To improve the quality of the approach and include a margin of error, the velocity noise error tolerance must be less than 8 feet per second. Flight test experience with the Lamps helicopter and the Harrier indicate that linear accelerations less than ± 0.1 g to ± 0.15 g are acceptable to the pilot during a precision approach and hover.

Another way to determine the requirement for 3 dimensional velocity accuracy when one knows or can approximate the aircrafts response transfer function to velocity commands is to determine the velocity command that results in an 0.1 g or 0.15 g acceleration. The maximum allowable velocity error must then be less than the computed maximum velocity command allowable. With a velocity response time constant of 3.3 seconds, a basic command update rate of 10 HZ, and a 0.1 g acceleration limit, one-half of the maximum allowable velocity error is 5.5 feet per second, which is less than the barely acceptable 8 feet per second error determined from the simulation analysis. To get a 5.5 feet per second velocity accuracy (1-sigma), the position measurement system must have a noise induced single sample error of less than 7.8 ft, if simple averaging over 2 seconds is used to compute velocity. For distances a few miles from the ship, where the aircraft has sufficient altitude and time to correct approach path errors, the control gains can be reduced, thus permitting larger velocity errors. Figure 9A shows the equation for maximum allowable velocity error as a function of the acceleration limit, and command update time.

The requirements for lateral and vertical position and velocity accuracy can be determined using analyses and simulations similar to the above. However, in addition to the acceleration limits, the flight path deviation errors allowed must also be considered in determining the position and velocity measurement accuracies required. For example, a vertical position measurement noise error of 7.8 feet (1 sigma) with a basic update rate of 10 HZ may result in vertical accelerations of less than 0.1 g, but may cause path errors that are unacceptable, especially at altitudes below 100 feet.

It would be desirable if one sensor could provide over the entire coverage sector, both position and velocity data of sufficient accuracy to provide smooth control acceptable to the pilot and path control errors that result in a safe and high recovery rate. When accurate velocity data is derived from the rate of change of position data, the accuracy requirements of the position measurement sensor become stringent. Figure 9B gives the basic relationship between position accuracy achieved and derived velocity accuracy. Figure 10A shows an approximation of the change in aircraft velocity in any one of the three dimensions for a time interval of one update period. The magnitude of the acceleration in g's caused by a change in velocity over a short time interval along any of the translational axes is approximated by the relationship shown in Figure 10B.

Figure 11 is a plot of the maximum allowable velocity measurement noise error as a function of the acceleration limit specified and the command update time interval for an aircraft with a velocity response constant of 0.3 (or a response time constant of 3.3 seconds). With a 0.1 G acceleration limit specified, the maximum allowable velocity measurement noise error is 11 feet per second for a 0.1 second command update rate. To have good flying qualities, the specified velocity measurement noise error (1-sigma) should be less than one-half the maximum allowable or 5.5 feet per second.

Figure 12 is a plot of the maximum allowable position error for a system that estimates velocity by averaging N successive position differences divided by the update time. The maximum allowable position error is plotted as a function of the number of velocity samples averaged, and the acceleration limit specified. For a 0.1 G acceleration limit and 20 samples averaged (2 second averaging interval), the maximum allowable position error is 15 feet. For better performance, a value of less than one-half of the maximum allowable should be specified for the one-sigma position noise error. Better filtering techniques and changes in the averaging or smoothing time will change the magnitude of the allowable position error. However, the averaging time cannot be increased without considering the effects of gusts and turbulence. It is to be noted that only the translational acceleration limits were used to determine the above mentioned accuracy requirements. Rotations and rotational rate limits and aircraft path following errors were not considered.

Of the three geometric techniques shown on Figures 6, 7 and 8, only the range, elevation, azimuth type can come close to achieving the accuracy required at the longer ranges, since the short baseline due to shipboard installation of both the triangulation or trilateration become extremely inaccurate at ranges of 20 times the baseline or approximately 800 feet. The short baseline triangulation technique has poor horizontal and vertical position and rate accuracy at long range, and must have additional range and range rate sensors, and vertical velocity or acceleration sensors for distances greater than 400 feet. The trilateration technique has poor horizontal, lateral and vertical position and rate accuracy beyond a distance of 400 feet. Moreover, this technique will be the most susceptible to multipath errors if implemented at microwave frequencies.

Figure 13 is a plot of the worst case horizontal distance and vertical errors as a function of range on a 3 degree glideslope for several error combinations of a R, Θ, ϕ system. A noise error of 0.1 degree in elevation angle and 10 feet in range would result in a vertical or height noise error of 32 feet at 3 nautical miles. The height error at the longer ranges is primarily dependent on the elevation angle error as long as the range error is less than 50 feet. To achieve the 1 foot three dimension position accuracy near the touchdown zone, the basic range accuracy must be 1 foot or better near touchdown.

Figure 14 is a plot of the worst case horizontal and vertical errors versus the angle errors for the triangulation system. At a range of 800 feet, the horizontal distance error is 60 feet for angle errors of 0.1 degree, and 30 feet for angle errors of 0.05 degrees. The vertical error is 5 feet and 2.5 feet respectively. Both horizontal and vertical errors increase rapidly as range increases.

Figure 15 is a plot of the worst case linear position errors as a function of range for a trilateration system with 40 foot baselines and a basic system ranging accuracy of 1 foot. At a range of 800 feet, the vertical and lateral errors are both equal to 40 feet, which corresponds to an azimuth and elevation angle error of 2.87 degrees.

The position and velocity preliminary requirements for a VTOL aircraft approach and landing system are summarized on Figure 16. The position and velocity data can be derived from a single position sensor system or a combination of position and motion sensors. When relative velocity is derived from the position sensor system, the accuracy requirements of the position sensor must satisfy both the position and velocity requirements. In most cases, the need to meet the velocity accuracy will place a more stringent accuracy requirement on the position sensor.

Candidate Sensor Systems

There are many alternative techniques which feature different operating frequencies from microwave to optical-infrared, different geometric techniques of position fixing by range and angle measurements from a single point or points on a short baseline available at the landing platform typically forty feet wide. Microwave systems offer the potential of attaining the ceiling/visibility objectives, but must be tested to show its capability of providing the in-close accuracy, especially in a severe multipath environment. Hybrid frequency systems with microwave and electro-optical (E-O) sub-systems can achieve the accuracy, but not the ceiling/visibility objective. Safety and pilot acceptance requires that the microwave to E-O transition be made smoothly, and with sufficient time and distance to allow the pilot to check the final system and decide whether to continue or discontinue the approach.

The results of the techniques investigation to date have been applied to identify promising system candidates. The preliminary system requirements, including such factors as coverage and accuracy, were used as criteria. The following candidates were identified as showing the greatest promise of meeting most if not all of these requirements:

1. K-band, FM/CW, or pulse radar-transponder ranging and single-point tracking.
2. Microwave scanning (MRAALS or MLS) triangulation, with DME ranging.
3. Microwave scanning beam (MRAALS or MLS) with DME ranging, and a laser close-in tracking.

The rationale for the selection of these candidates is shown in Figure 17. The K-band radar-transponder was selected because it shows promise of satisfying the combined requirements of low weight/space, accuracy, coverage in clear and adverse weather, and also coverage during wave-off and take-off. Precision ranging equipment using FM/CW modulation are being developed and will be tested for accuracy in a multipath environment to determine whether the 1 foot range accuracy can be met at short ranges.

The microwave scanning beam triangulation with DME ranging is attractive because it expands the capability of existing (AN/SPN-41, MRAALS) or developmental (MLS) systems, thus reducing the problems of future implementation and system compatibility. However, tests and analyses shows that the horizontal and vertical position and rate accuracies are good at short ranges, but are not adequate for ranges greater than 400 feet when obtained from triangulation along even though the signals can be acquired at much greater ranges. Range data from DME equipments used with MRAALS or MLS may be adequate at the longer ranges, but the range data, and especially the range rate data will not be accurate enough for a decelerating approach to the point where the triangulation data can be used. Thus another source of accurate range, or low speed velocity and altitude must be added to augment the position and rate data provided by the scanning beam triangulation with DME. Potential candidates to provide accurate range or low speed velocity data are a DME with better range and range rate accuracy than currently available from TACAN or MRAALS, a low airspeed sensor, or a one-way range rate technique added to the scanning beam signal format as proposed by AIL Inc. The triangulation technique will require two antenna scanners separated by a baseline of approximately 40 feet. The triangulation technique will not provide coverage during wave-off and take-off because of ships superstructure blockage. Guidance during wave-off and take-off must then be accomplished using data provided by existing airborne motion/heading sensors, or be performed visually by the pilot.

The microwave scanning beam with DME ranging and a shipboard laser tracker is another candidate that will extend the use of existing or developmental approach guidance systems such as AN/SPN-41/ARA-63, MRAALS and MLS. Approach guidance at the longer ranges will be

provided by the microwave system augmented by airborne motion sensors. The laser tracker will acquire and provide guidance from a distance between 1 and 0.25 nautical miles depending on visibility and aircraft type. The point of acquisition by the laser tracker must occur at a distance and altitude large enough to allow the pilot sufficient time to safely discontinue the approach to landing if the laser tracker does not acquire the aircraft and the pilot is unable to visually continue the approach. Thus the ceiling/visibility operational goals of zero ceiling/700 foot visibility will not be met by an electro-optical approach. The microwave scanning beam with laser tracker implementation makes maximum use of existing avionics, but assumes that tactical data link equipment will be available for two-way transfer of information required for the final approach, hover and landing.

While existing guidance system program is moving toward fulfillment of its objectives, a listing of the still open objectives is in order:

a. Achievement of 1 ft position and 1 ft/sec velocity accuracy in the final hover and descent volume.

b. Selection of a guidance system technology and configuration to achieve accuracy requirements over the entire coverage volume.

c. Compatibility of guidance system with existing aircraft receivers so that minimum modification is required.

d. Successful interface of guidance system information with flight control and display system.

Conclusion

Current analysis and testing to date indicate that several candidate position guidance systems show promise of meeting the coverage and accuracy requirements sufficient to accomplish an automatic or piloted approach, hover and landing of a VTOL aircraft on Navy ships.

FIGURE 1.
APPROACH PROFILE VTOL VS CTOL

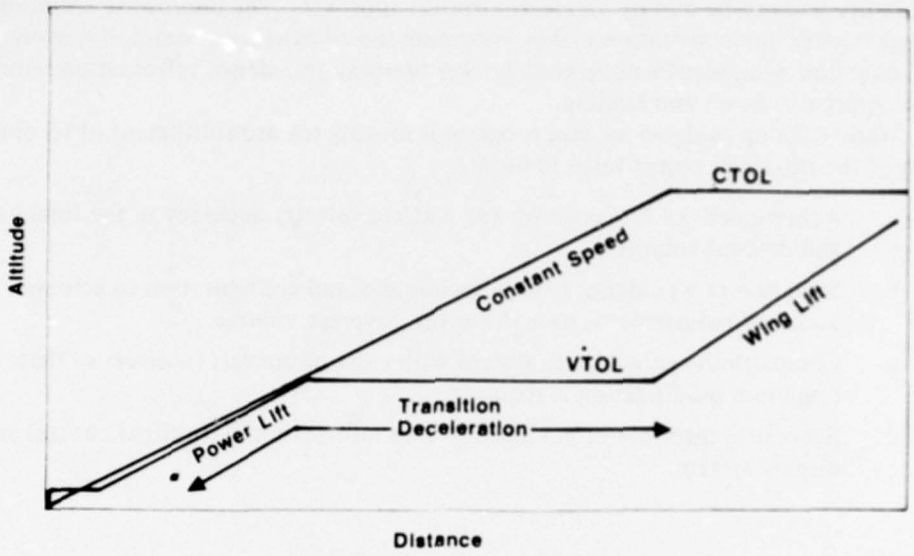


FIGURE 2.
APPROACH ENERGY DIAGRAM VTOL VS CTOL

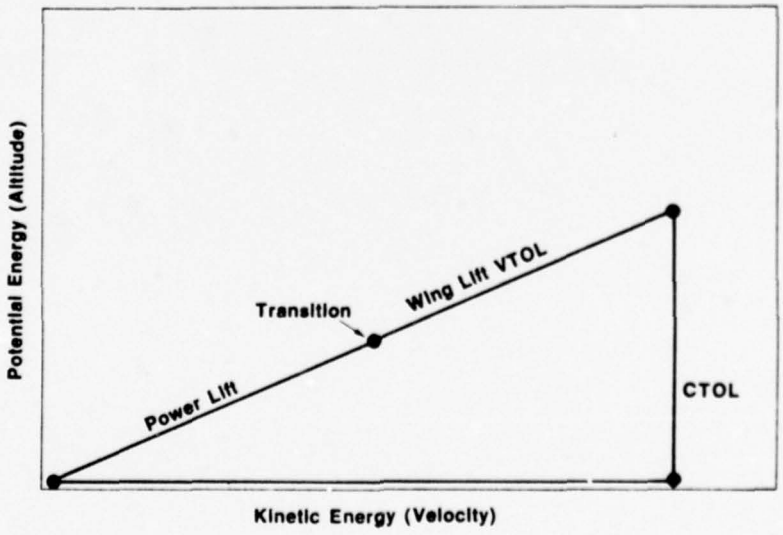


FIGURE 3.
GENERAL REQUIREMENTS

- Coverage – $\pm 40^{\circ}$ azimuth coverage at outer range
  2° to 20° elevation at outer range
  AZ/EL coverage in-close sufficient for guidance to touchdown
  Minimum operating range = touchdown point
  Maximum operating range ≈ 3-5 nautical miles
  Wave-off coverage desired
- Ceiling Minimums – 0
- Visibility Minimums – 700 feet
- Sea State – Up to Sea State 5
- Rain – Heavy Rain up to 16 mm/hr
- Shipboard landing deck size – 40 ft × 40 ft minimum
- Data quality – Sufficient for piloted and automatic landings

FIGURE 4

SHIP AND VTOL MOTIONS AND THE LANDING PROBLEM

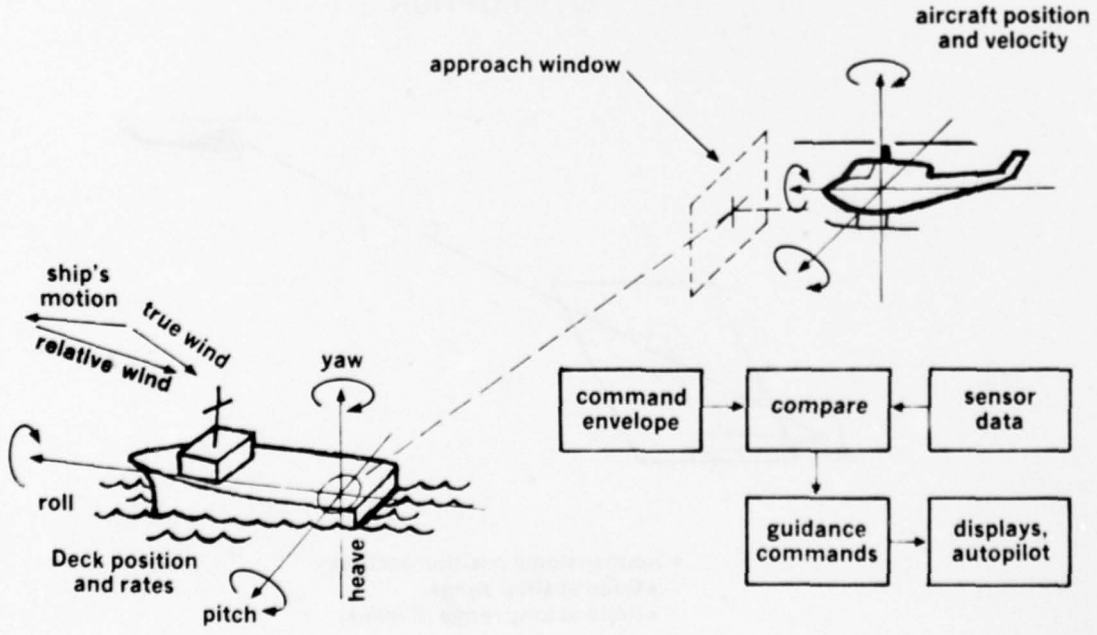


FIGURE 5.
VTOL APPROACH AND LANDING CONTROL SYSTEM

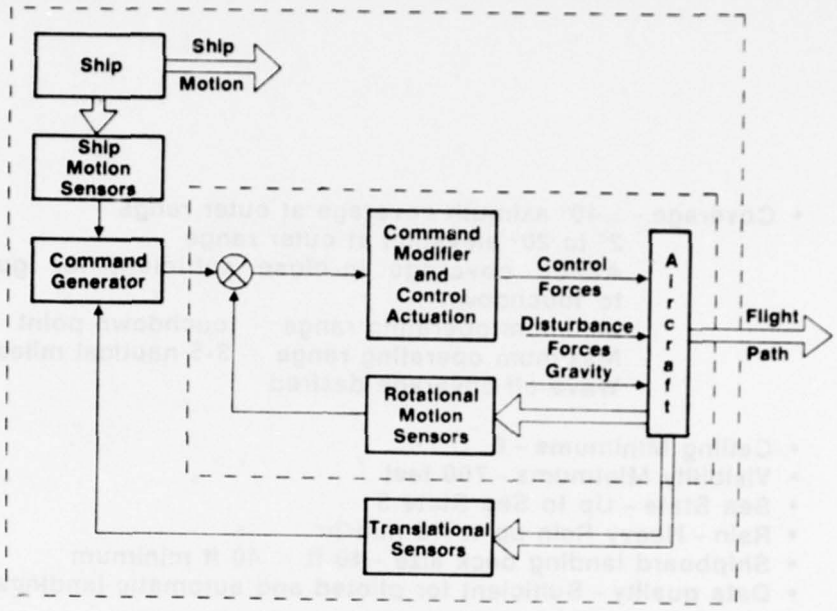
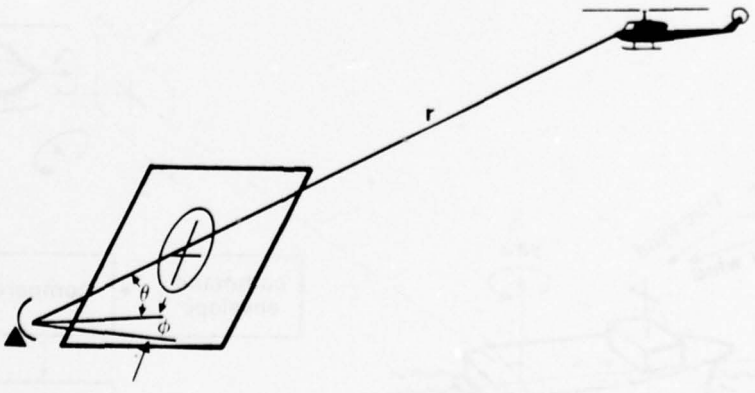


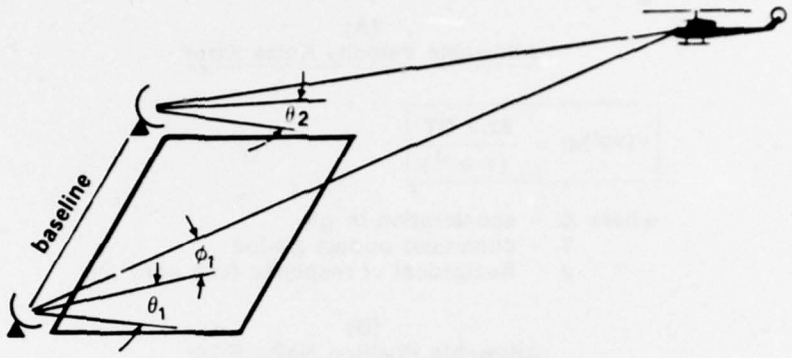
FIGURE 6

ϕ , θ r OPTION



- 3-dimensional position accuracy
  - Good at short range
  - Good at long range (5 miles)

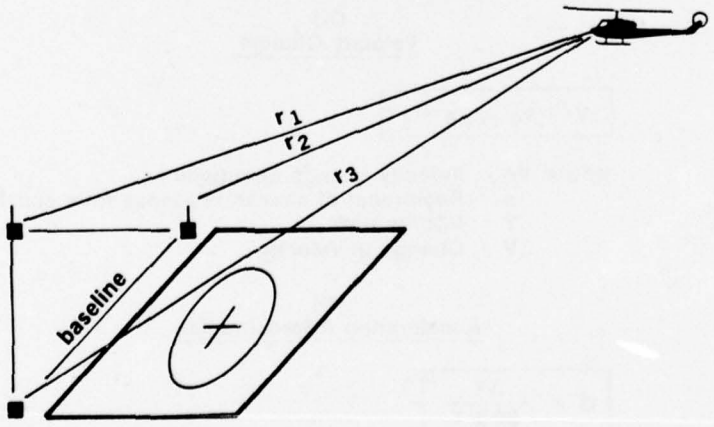
FIGURE 7
TRIANGULATION (SHORT BASELINE)
$\phi_1, \theta_1, \theta_2$ OPTION



- Accuracy is a function of the baseline 3-dimensional position accuracy
  - Excellent at short range
  - Poor at long range (greater than 20X baseline)

FIGURE 8
TRILATERATION (SHORT BASELINE)

Range, Range, Range Option



- Accuracy is a function of the baseline 3-dimensional position accuracy
  - Good at short range
  - Poor height and lateral at long range (greater than 20X baseline)

FIGURE 9

(A)
Allowable Velocity Noise Error

$$\sigma(\text{vel})_m = \frac{32.2\ GT}{(1-e^{-aT})}$$

where G = acceleration in g's.
T = command update period
a = Reciprocal of response time constant

(B)
Allowable Position Noise Error

$$\sigma(\text{pos}) = \sigma(\text{vel})\ \frac{NT}{\sqrt{2}} = \frac{32.2\ T^2\ GN}{\sqrt{2}\ (1-e^{-aT})}$$

where N = number of sample intervals averaged to compute velocity.

FIGURE 10

(A)
Velocity Change

$$\Delta V = V_c\ (1 - e^{-aT})$$

where Vc = Velocity change command
a = Reciprocal of aircraft response time constant
T = Update time
ΔV = Change in velocity

(B)
Acceleration Approximation

$$G = \frac{\Delta V}{32.2\ T}$$

where G = acceleration in g's.
T = update time.

FIGURE 11.
MAXIMUM ALLOWABLE VELOCITY MEASUREMENT NOISE ERROR

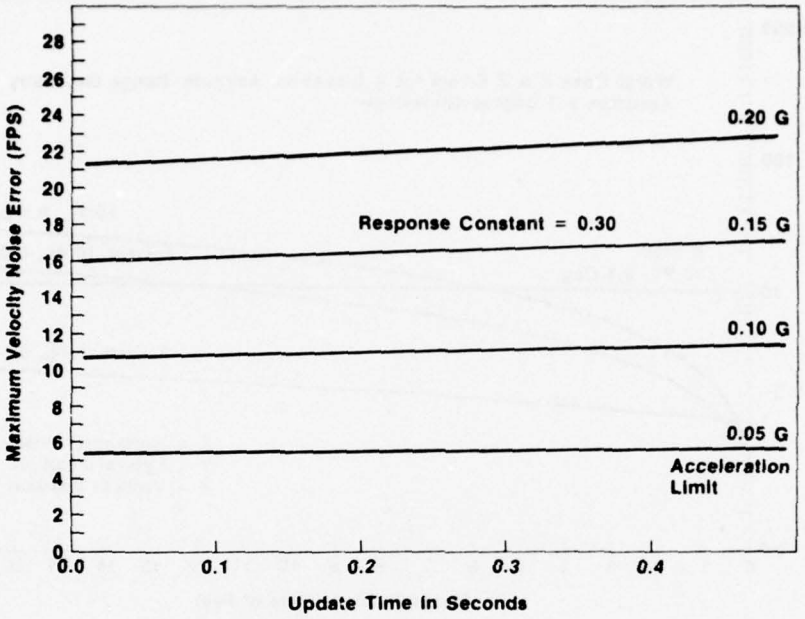


FIGURE 12

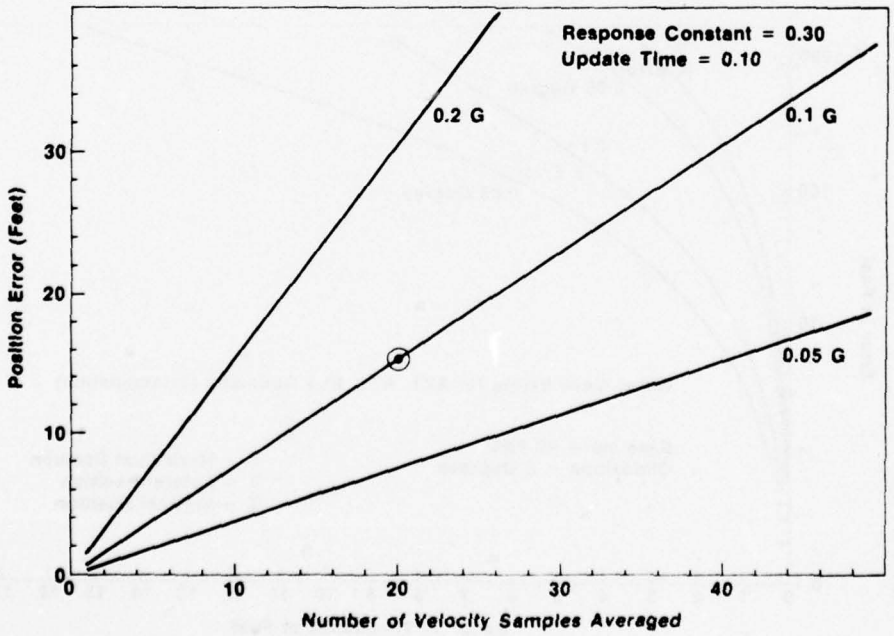


FIGURE 13

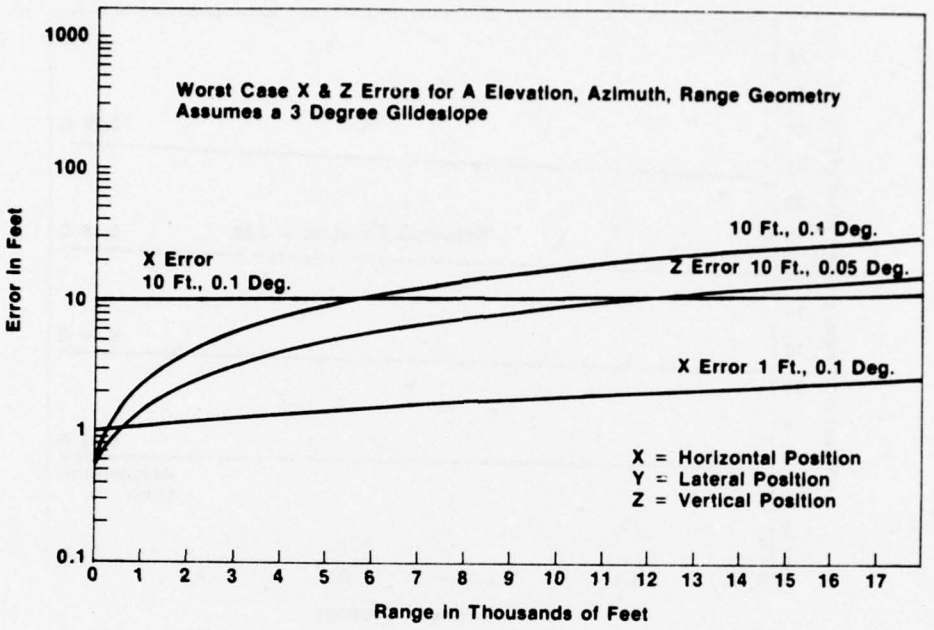


FIGURE 14

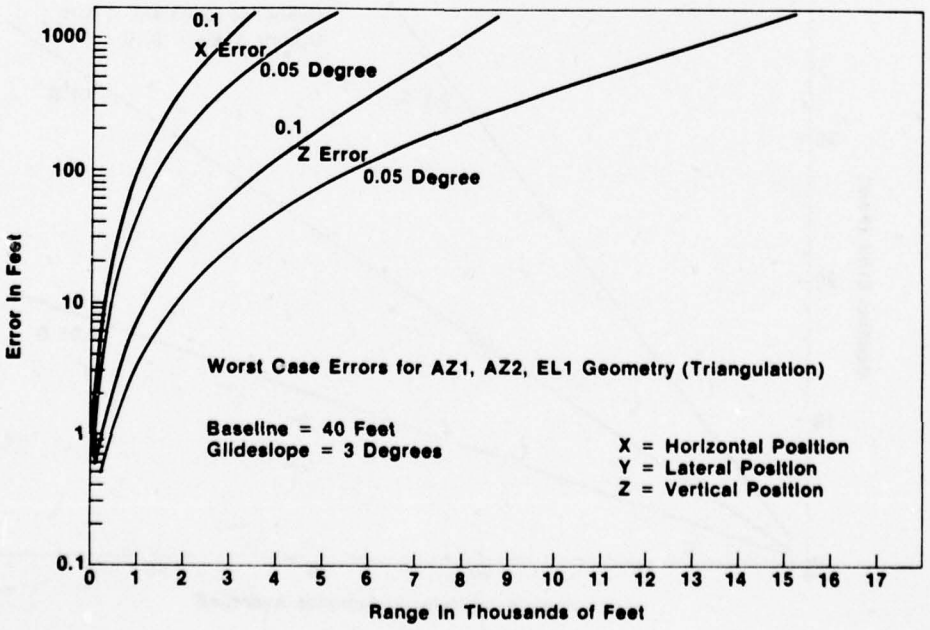


FIGURE 15

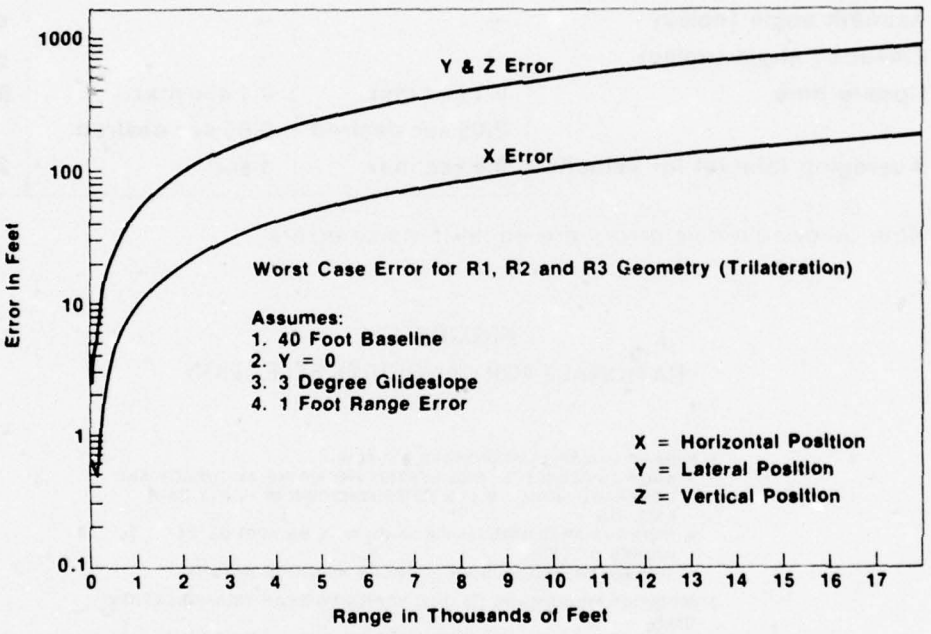

1000
100
10
1
0.1
Error in Feet
Y & Z Error
X Error
Worst Case Error for R1, R2 and R3 Geometry (Trilateration)
Assumes:
1. 40 Foot Baseline
2. Y = 0
3. 3 Degree Glideslope
4. 1 Foot Range Error
X = Horizontal Position
Y = Lateral Position
Z = Vertical Position
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
Range in Thousands of Feet

FIGURE 16
TENTATIVE POSITION AND VELOCITY SENSOR ACCURACY REQUIREMENTS

	Range		
	0-300 ft	300-3000 ft	3 nmi
Horizontal position noise (1σ)	1 ft	1 ft + .02 (R-300)$^{1.55}$	100 ft
Lateral position noise	1 ft	1 ft + 0.003 (R-300)$^{1.8}$	—
Vertical position noise	1 ft	1 ft + 0.003 (R-300)	—
Horizontal velocity (noise)	1 fps	1 + .002 (R-300)$^{1.5}$	10 fps
Lateral velocity (noise)	1 fps	1 + .002 (R-300)	10 fps
Vertical velocity (noise)	1 fps	1 + .002 (R-300)	10 fps
Azimuth angle (noise)	—	—	0.1 deg
Elevation angle (noise)	—	—	0.1 deg
Update time	0.1 sec max.	0.1 sec max.	0.1 sec
	0.05 sec desired	0.05 sec desired.	
Averaging interval for velocity	0.5 sec max.	1 sec	2 sec

Note: Allowable bias errors are equal to noise errors.

FIGURE 17
RATIONALE FOR CANDIDATE SELECTION

1. K-BAND RADAR-TRANSPONDER SYSTEM
   - SHOWS PROMISE OF ONE SYSTEM PROVIDING ACCURACY AND COVERAGE FROM 5 MILES TO TOUCHDOWN IN HEAVY RAIN AND FOG
   - ANTENNA APERTURE (SHIPBOARD) WILL BE APPROX. 24 INCHES OR LESS
   - SHIPBOARD PROCESSING REDUCES AVIONICS WEIGHT
2. MODIFIED MICROWAVE (15 GHz) SCANNING BEAM TRIANGULATION; DME
   - TECHNIQUE CAN BE COMPATIBLE WITH MLS OR MRAALS
   - AIRCRAFT EQUIPPED WITH MLS WILL REQUIRE ONLY A MODIFIED PROCESSOR
   - DISADVANTAGE IS THE REQUIRED ADDITIONAL SHIPBOARD SCANNING ANTENNA
3. MICROWAVE SCANNING BEAM WITH LASER TRACKER; DME
   - HYBRID SYSTEM COMBINES RAIN/FOG PERFORMANCE OF MICROWAVE WITH PRECISION OF ELECTRO-OPTICAL
   - NAVY AND OTHER MILITARY AIRCRAFT WILL BE MLS EQUIPPED; MAXIMUM USE OF ON-BOARD EQUIPMENT
   - HYBRID SYSTEM REDUCES THE STRINGENT ACCURACY REQUIREMENTS OF THE MICROWAVE SECTION
4. ELECTRO-OPTICAL SYSTEM WILL NOT PROVIDE THE COVERAGE AT LONG RANGE IN FOG

DISCUSSION

LCDR David Poole: Have you given any consideration to using the equipment commonly on board the aircraft like fire-control radar and bombing radar coupled with the aircraft's inertial platform for the long range resolution combined with a high resolution in-close radar to provide the terminal approach coverage?

Frank Morris: Yes. The problem is that the majority of these systems that you mentioned can provide one with some information for the approach guidance, but the inaccuracies in them are too large. We're considering in the final landing phase of having three-dimensional position accuracies of about a foot in the x, y and z dimensions due to noise and probably about the same values from bias. Even systems such as TACAN have a conservative accuracy of 100 feet. The primary system would have high accuracy, but we could use all these other inputs as a redundant backup and check on the main system. Even in our inertial systems, the measurements that can obtain from the ship relative to pitch and roll may not be accurate for making the corrections to our readings. We may have to provide our own roll, pitch and heave measurement systems.

Duane McRuer: I have a couple of questions. Following up on this other question, why can't you occasionally update an airborne inertial system and continue the approach to some minimum range? I don't fully understand the zero-zero requirement that has been stated here. The approach is presumably in a Category 3 sea system, and there must be some visibility.

Morris: Zero-700 (Zero ceiling and 700 feet or 1/8th mile visibility) is what we're talking about. The problem is that if you're intending to control the V/STOL vehicle through the transition with an inertial system, you must have systems better than presently in the Harrier. The update of an inertial system is difficult if you don't initially have an accurate position.

McRuer: You have to update it relative to the ship. That can be done during a period of time when the aircraft is fairly far out, which allows you to take many measurements over a period of time. If you smooth or interpret these measurements properly, the accuracy level should be pretty good. Finally, the terminal phase would be done visually.

Stan Miyashiro: Admittedly one can do that, but the small ship does not have the capability of updating information between the ship and the incoming aircraft.

McRuer: Since you have no capability at present of doing this, you're talking about a system that is yet to be designed. Most of the statements being made here indicate that the chances are quite good for having a relatively high-grade inertial system in the aircraft. The need to update it implies that you do require some sensor on the ship to provide ship-to-aircraft data quite precisely for a period of time during the terminal phase. If you could observe it for 20 seconds, you would get real good data in the time period by averaging from a number of radars.

Miyashiro: That would be true if the ship had that capability. Most of these small ships that we have don't have that capability yet.

Morris: Also, I don't think you're going to trust the inertial system for 0/700 terminal approach operating conditions.

McRuer: You can trust an inertial system such as currently installed on automatic landing systems or ordinary (CTOL) airplanes. We can essentially land the airplanes with the inertial system plus the radar altimeter using what amounts to terminal fixes off the ILS on the way in.

Morris: I think that your point is: "Why not use a combination of systems that are already likely to be available for other reasons?" I would consider the inertial (system) as a backup for something like this. If you're really designing for a total Automatic Landing System (ALS), you are going to include some type of redundant system on board the airplane in any event.

McRuer: O.K. Now one of the systems that you would have on board the aircraft would be very close to the inertial system by itself. Then all you need is to provide it with an update process.

Robert Flynn: I'd like to play the comment back on the use of inertial systems for automatic landing. I'd state it in another way since the standard ILS beam that we use is not all that good. In fact, in this country, there are only a few CAT-III facilities and it is true that these use inertial platforms. They're used more in a smoothing sense since the beams are noisy; for example, there is a lot of hash on the beam signal during a low overflight. An inertial system allows the noise to be removed, but still you're tied in a long term sense, fifteen seconds or more, to the beam. These remarks are relative to systems that are certificated.

McRuer: I know what you're describing, since I have been involved in some of those too. Basically the inertial system is acting as a lovely filter for the ILS, but the ILS is acting as a terminal fix point on the inertial system as well. That's what I have essentially been proposing here.

Jack Beilman: As a side comment, I mentioned yesterday that we're already doing some of this on the X-22, but not the zero-zero situation since we're not that fancy. We're only using a four Hertz update rate without anything fancy onboard the airplane. There are three separate accelerometers in x, y and z which fill in the gaps on the information rate. Based upon what we've seen so far, we're coming in hooded to a 100 foot hover with a position essentially over the centerline of a 150 foot wide runway. So I don't think that these esoteric or real fancy inertial packages are necessarily required research.

Morris: Again, we're talking about landing zero-zero on a forty by forty foot platform. Are you ready to do that?

Beilman: No, I didn't say that.

Charles Abrams: I'd like to make a comment relative to Mac's statements. These small ships that we're talking about will most likely not have any inertial reference. How do you align the inertial system on the aircraft?

McRuer: Are you asking me?

Abrams: Yes.

McRuer: Well, all I want the inertial system on the aircraft to do, assuming in the first place that it's a redundant system so that we have reliable sensors, is use some of the latest ideas such as the Boeing ISADS for tying the flight controls with the inertial system. The problem, Charlie, is only one of updating the inertial system relative to the ship.

Abrams: But if you don't align it initially, you must admit that you won't have a reference on the ship. It won't be a sensor.

McRuer: I don't care! All I need to know is that I can fly the airplane around for a few seconds relative to the ship. If I have a good shipboard sensor, then errors on the shipboard sensor can be relatively large provided I observe it for a period of time. In that way, I can make a tradeoff between the time of observation and the accuracy of the observation. Finally, I propose to take the terminal error out visually. I don't see any requirement for zero-zero operations.

Abrams: Well, it's not an absolute requirement. It's 0/700.

McRuer: O.K., then that means that you can do something visually.

Abrams: Yes, you have 700 feet of visibility.

McRuer: You can remove considerable error in 700 feet of visual range.

Morris: One last comment.

LTCOL Iles: I'd just like to make one comment. One of the things which we found that really enters in this argument is the requirement for MCON on a ship. It is related, if I'm interpreting your remarks correctly, to keeping the ship as silent as possible and being able to place that airplane in the ballpark with its self-contained system. That approach gives the task force or the ship a distinct tactical advantage that is already badly needed. I believe that war games and similar tactical exercises have shown that once the ship opens up with any sort of (electro-magnetic) radiator, especially before he has to or before he's threatened, it really reduces his chances of survival. Finally, it would seem that an all on board system would be the way to operate.

NAVTOLAND AND FLYING QUALITIES

by

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INTRODUCTION - PROGRESS OR MARKING TIME IN V/STOL OPERATION?

Five years ago, an AGARD Working Group on V/STOL Displays for Approach and Landing observed ". . . it is an unfortunate fact that no true VTOL aircraft has an effective poor weather capability, particularly into restricted sites, at the present time." [1] At the present time, that is, in 1977, one must yet observe that an effective poor weather capability still lies somewhere in the future of the V/STOL operations.

There may be a number of reasons for the apparent "marking of time". In the first place, the AV-8A Harrier which had become operational only a year or so before the AGARD report (No. 594) is still the only operational aircraft in the U.S. and U.K. today. The limited flight control system capability of the AV-8A, which had originally been designed with no stability augmentation system and was subsequently equipped with only a rate-damping stabilization system, dictates the current weather minima of 400 foot ceiling and one nautical mile visibility. The pilot workload is the primary limiting factor. With the pilot providing the attitude-stabilizing, position-fixing, height-controlling and deck motion-predicting functions simultaneously or within a very short span of time. The conversion flight, or transition to powered flight, and subsequent hover and landing must be accomplished in Visual Meteorological Condition (VMC). The first of the concerted, full-scope efforts to cull out the "lessons of some six years of operation of the world's first operational jet V/STOL aircraft", i.e. AV-8A, took place last December (1976) in Norfolk, Virginia. Under the co-sponsorship of the Naval Safety Center and the Naval Air Systems Command, Harrier pilots of the U.S. Navy, U.S. Marine Corps, Royal Air Force and Royal Navy and U.S. and U.K. V/STOL technology experts held workshops on: flying qualities and performance; human factors/escape systems; operational safety factors; and pilot selection and training. The discussions attested to the AV-8A pilot's workload problems in Instrument Meteorological Condition (IMC) and pointed up the need for improved pilot aid in much the same area postulated previously such as in the AGARD Report 594.

The second problem is that the all-weather, precision landing guidance system has been an exclusive possession of the aircraft carriers. The

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helicopter carriers (LPHs) have been equipped with SPN-35 Precision Approach Radar (PAR) but this voice-controlled system does not enable V/STOL conversion flight in IMC. Nearly two hundred of so-called aviation facility ships currently have no more than the TACAN navigation aid. As the AGARD Working Group reported, "there is a generally held opinion that operation of VTOL aircraft under poor weather conditions should be fundamentally more safe than CTOL aircraft by virtue of the former's ability to fly slowly and stop if necessary".[2] Beside being obviously unaware of the engineering complexity and human factors difficulty, "to fly slowly and stop" the characteristically unstable V/STOL machines and generally more constrained V/STOL operational environment than that for CTOL, those who hold the above notion are ignorant of the fact that the stop-and-go flying in adverse weather actually requires more continuous and accurate guidance than the CTOL flying of constand speed and glide slope. While the CTOL final landing task is to maintain the aircraft control parameters in the conditions achieved at the commit-to-land "window", the V/STOL landing task in the same flight regime is a continuous and generally high workload maneuvering task about a "pin point" landing spot. In vertical landing, the typically small landing platform or site becomes obstructed from the pilot's field of view, even in helicopters. In this respect, the pilot of V/STOL aircraft, especially the streamlined high-performance ones, faces virtually blind landing even in clear weather. The importance of landing guidance system is evident in the fact that helicopters generally equipped with relatively more advanced stability augmentation system than the AV-8A are still constrained to weather minima similar to those for the AV-8A when landing on aviation facility ships which are not provided with approach and landing guidance systems.

There has been a rather limited amount of V/STOL flight research conducted in the last several years to obtain necessary data for advancing the all-weather V/STOL operations. The VAK-191B project, besides exploring the lift plus lift/cruise configuration concept from many technological aspects, uncovered some interesting and important, dichotomous problems of flight control system charactertistics for IMC approach and VMC landing. However, the experiments were conducted all in VMC and in non-operational environment. The current phase of the X-22A flight research has just begun to investigate the flight control and display interfacing parameters in IMC approach to a landing, with the AV-8B aircraft charactertistics programmed into its variable stability system and a head-up display (HUD). Royal Aircraft Establishments at Farborough and Bedford are currently experimenting with a Harrier T MK 2 equipped with a programmable HUD to improve shipboard operational capability of the Sea Harrier.

The V/STOL missions for the seaborne Navy is still in the formative stage. The Navy helicopter community has long and ably refuted Wilbur Wright's desparaging remark about the worth of helicopter: "the helicopter does, with great labor, only what the balloon does without labor" and is going on to develop a capability like the Light Airborne Multipurpose System (LAMPS). The Marine Corps has established a beachhead in V/STOL warfare with the AV-8A and shortly AV-8B. For the Navy, however, the first V/STOL aircraft, the Type "A", is currently being conceptualized toward late 1980's operational capability. So, beyond the mere identification of several major warfare areas applicable to Type "A" and the general notion, as might be paraphrased from the AGARD Report 594, that one of the attraction

of the V/STOL aircraft for military application is its ability to operate into and out of tactical sites and non-aviation ships which may be remote from conventional airfields and aircraft carriers, the potential Navy V/STOL missions are yet to be defined. The Navy V/STOL technology efforts then need to be pursued not only by projecting lofty enough operational capability goals but also to provide operational planners with V/STOL - unique options to expand their tactical repertoire.

While a look at the V/STOL operational capability might hint little progress, considerable effort has been made to plan and initiate R&D programs toward advancing the Navy's vertical takeoff and landing capability. Indeed, the authors of the AGARD Report 594 should be pleased that the substance of the conclusions and recommendations of the report is being addressed in one concerted project in the Navy. The NAVTOLAND project[3], which stands for the Navy vertical (and short) takeoff and landing capability development, is to correlate and integrate the development of all systems and techniques which are involved in enabling the pilot to fly V/STOL aircraft onto the Navy and Marine Corps ships and tactical sites.

NAVTOLAND PROJECT

PROJECT GOAL

Figure 1 illustrates the NAVTOLAND project goal of improving the previously mentioned, current VMC operational limitations in terminal area to the all-weather, instrument-flight operational capability. The project goal of zero ceiling and 700 foot visibility corresponds to the obscured ceiling and 200 meter Runway Visual Range (RVR) condition of ICAO Category IIIA. Primary reasons for setting the goal at Category IIIA rather than the ultimate, Category IIIC, i.e., zero-zero weather, are:

1. A completely automatic flying capability which may be required for the zero-zero condition may not be required or desired for all operational situations at costs imposed on the aircraft;

2. A guidance system to provide Category IIIA capability would be accurate enough for Category IIIC operation as well;

3. The development of flight control and display software for Category IIIA operation would provide the basic control laws required for automatic flying, thus merely leaving hardware implementation which must be done for each specific aircraft anyway;

4. Technically speaking, working with the pilot-controlled "manual" operation, if systematically pursued, would present wider spectrum and dynamics of varibles for more thorough evaluation of problems to be solved;

5. That high level of "manual" landing performance would be a prerequisite to successful automatic operation, should we need to work up to the latter, for independent monitor/back up/emergency, etc. One of the problems in the automatic-capable, current carrier landing system is that the independent monitor system is of one-fifth accuracy of the main system. This is not adequate for required main system parity check as well as, and perhaps more importantly, for pilot confidence.

The project goal for rough sea operation is Sea State 5 which corresponds to the significant wave height band of approximately eight to 13 feet. The current operational capability of the Navy and Marine Corps helicopters and the AV-8A with respective operating ships is generally Sea State 3 (significant wave height band of four to six feet). In practice, operating limits are set, for example, in the SHIPBOARD OPERATING BULLETIN of various aircraft, in terms of ship motions, in angles (degrees), of particular type ships. The Sea State is used here to indicate generalized operational capability situations.

To determine or define what environmental limits should be used for a given operational requirement is not a simple operational analysis task. If an extreme environmental condition, in which a weapon system might be called to perform even once in its lifetime, is critical to the particular tactical or warfare mission accomplishment and is judged to be worth the expenditure of the money and effort, then that condition would be the target. How does one anticipate, let alone plan for such an event? Hence, a very all encompassing term "all weather" is normally and conveniently used. There has been much inquisitiveness, particularly among high-level, programming and funding decision makers, as to just how much "all weather" is required and then how much is that requirement needed. The NAVTOLAND project environmental goals were arrived at through a comprehensive analysis as represented in figures 2, 3 and 4. A survey of occurrences of weather and sea state conditions was made over world's major sea lanes which should be valid for probability of Navy V/STOL operations.[4] In figure 2, except for a spot off the Scandinavian coast, Ocean Surveillence Vessel (OSV)MIKE, the 400 foot ceiling and one nautical mile visiability weather occurs on annual average basis approximately 20% of the time. This means that with the current V/STOL operational capability the fleet cannot operate 20% of the time in a year on annual average basis. In the worst-weather quarter of the year, data indicate that the frequency of occurrence goes significantly higher than that. The obscured ceiling and 1/4 mile weather, which is slightly better than the NAVTOLAND goal of zero ceiling and approximately 1/8 mile visibility, is inserted in the 400 and one block and shows that in these areas the fleet could reduce the non-operational situations

down to about 6% if the NAVTOLAND systems capability were provided. It is intersting to note that there is little difference in the frequency of occurrence between the 400 and one and 200 and 1/2 weather situations. It is, therefore, meaningless to set a goal of advancing from the 400 and one to 200 and 1/2 capability. There seems to be a significant, potential gain in operational capability when one aims to improve to the NAVTOLAND advocated goal.

Figure 3 presents an overland example of weather situation, which might confront tactical site operations of the V/STOL aircraft. In this typical European highland area, the 300 and one weather can occur on an annual average of about 30%. In early morning hours, this weather situation characteristically increases to approximately 50%. Data were not available, during the analysis, for the NAVTOLAND goal situation. However, the 30-50% non-operational condition indicates a need for a substantial improvement of the system capability.

A comparison of the annual average, percent frequency of occurrence of the Sea State 3 and 5 conditions in world's ocean areas known for high seas which are also major sea lanes is shown in figure 4. The graph indicates a possible reduction of non-operational conditions from approximately 65% down to 15% by achieving the NAVTOLAND capability of Sea State 5.

NAVTOLAND COMPONENTS

NAVTOLAND is a system integration project; and the system to be integrated is the vertical takeoff and landing operation. This means that the V/STOL aircraft and the platform from which it operates, whether on ship or in tactical site, are the two terminals between which the NAVTOLAND project components or subsystems (figure 5) provide interfacing functions to close the loop of operation. The NAVTOLAND project looks at the aircraft from the standpoint of those aircraft design parameters that affect its control in the vertical takeoff and landing flight regimes. The basic aircraft stability characteristics and the ground-effect induced thrust variation problems are very much specific to a given aircraft type; the NAVTOLAND task is not to solve problems of a specific aircraft but to assess and attempt to generalize data as inputs into the flight control laws development. With the pilot in the control loop, even in a possible automatic operation, handling qualities and the out-of-cockpit field-of-view become critical parameters (i.e., input variables) in the loop. The handling qualities, which is the subject of this workshop and the main underlying theme of this paper, will be put into the NAVTOLAND perspective further on in this paper. The flight control and display systems are principal pilot aids in the aircraft. The data-handling avionics is the aircraft terminal of the link to the platform. The media for the link are the air traffic control (ATC), approach and landing guidance signals and visual cues emanating from the platform. Various aviation and aviation-facility (formerly, non-aviation) ships and tactical landing sites provide

platforms for the ground terminals of guidance sensors and for visual landing aids (VLA). The Landing Signal Officer (LSO) and Landing Signal Enlistedman (LSE) are platform based human elements in the loop. The helicopter hauldown rapid securing device for LAMPS MK III or a potential, similar securing device for the V/STOL against severe motions of smaller ships are the final link in the aircraft-ship interfacing loop. Not shown in figure 5 but nonetheless important NAVTOLAND subsystems as components of the guidance link are low-speed sensor and ship motion prediction system.

NAVTOLAND PROJECT AND FLYING QUALITIES

What does flying qualities, the topic of this workshop, mean to the NAVTOLAND project and its components or vice versa? It is assumed herein that the workshop title is synonimous to the also often used term handling qualities. Cooper and Harper define handling qualities as "those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role". Figure 6 was taken from a Lamar and Neighbor paper in AGARD Conference Proceeding No. 119 and depicts handling qualities factors and the relationships of these factors as seen by Cooper and Harper. Lamar and Neighbor explain: "From (the above) definition it can be seen that handling qualities involve those factors which affect the pilot workload (ease) and performance (precision) of the task".5 Since the functions of the NAVTOLAND developed capability or "system" is to aid the pilot in "easying" the workload and achieve "precision" in the critical landing performance, the NAVTOLAND "system" must have its position somewhere in the loop of the handling qualities factors relationship. Figure 6 obviously assumes that appropriate sensors, hardwares and softwares would be provided to close the loops of relationships among various factors. For example, the aircraft movement would have to be detected and measured by position, motion and speed sensors, data-processed and displayed before the pilot can receive that information and actuate the controls for a new phase of aircraft movement. Without the consideration of such interfacing subsystems, the handling qualities specialist, if there ever is a true such specialist, may continue to produce apparently (or perhaps partially) valid handling qualities data operating on a single variable of aircraft stability and control characteristics against experimental conditions of environment and assuming near perfect constants for information to be presented to the pilot. Unrealistic or invalid result of such simplistic approach would be more detrimental in the V/STOL operation, where both the R&D and operational experiences have shown highly complex interfacing of the factors as well as some dominant roles of displayed and externally available information along with a fundamental needs for substantial augmentation of the primary controls.6 Lamar and Neighbor point out the "major problem confronting the handling qualities engineer that the effects of these factors cannot be isolated and the investigator must be careful to account for the remaining factors in such a way as not to obscure the effects being studied".7

In figure 7, the NAVTOLAND "system" components are integrated into the Cooper Harper chart which has been somewhat simplified to avoid clutter. For the vertical takeoff and landing operations, the landing platform has been added in the AIRCRAFT ENVIRONMENT column. In the NAVTOLAND flight regime of aircraft and platform (ship/site) interface, the aircraft movement factor must be "filtered" through or superimposed on the landing platform size and motion factor before pilot receives this motion information. The aircraft securing system, possibly required for rough sea operation from small ships, is an almost exclusive direct physical relationship between the aircraft and the platform.

The visual landing aids, electronic guidance systems and ship motion prediction system sense, translate and generate signals of the aircraft-platform motions and transmit to the information factor in the COCKPIT INTERFACE column. Both the electronic guidance systems and ship motion prediction system generated data must be transmitted through the data link devices up to the aircraft. In the aircraft, either the NAVTOLAND-developed or -shared avionics receives, decodes and sometimes performs additional computations to the signals received from the ship. The processed data are then fed into symbol generator for appropriate format for displaying on selected cockpit instruments or CRT (Cathod Ray Tube).

A very important pilot aid information in the powered-lift low speed and hover flights, the low speed sensor derives data from the aircraft movement factor and sends the data to the information factor, or often to the display element for integration of the aircraft speed into other position and motion data.

It should be obvious even in a symbolic representation of the handling qualities factors relationship that all of the information coming from these various data derivation sources must be well coordinated and integrated when the pilot receives them out of the information factor block, because that link is the sole source of positive control guidance he receives before he makes his instantaneous action on the controls. By the way, in the NAVTOLAND version of the handling qualities factors chart, the (cockpit) field of view is added in the information factor block. As discussed in the introduction section of this paper, the field of view is very critical in pilot's acquisition of external visual cues.

It is also important to note that the other NAVTOLAND component block, the flight control, operates between the aircraft stability and control characteristics and a given aircraft state factor and the principal controls factor, thus independent of the information loop. The only exception is the automatic operation in which the main control guidance loop is diverted and fed into the flight control block, with the information and pilot loop becoming the secondary and monitoring role. That the information (i.e., display) loop and the flight control loop operate separately when the pilot is in the manual control operation loop; that the ever-adaptable but also rapidly-degradable human pilot is the mixing gorund for these two separate loops; and that the traditional

developmental approach of indivisual systems (i.e. displays and flight controls) suboptemizations has not presented significant problems in the past CTOL landing capability development and therefore has not contributed toward a development of structured (i.e., generalizable and replicatable) methods of assessing the integrated display and flight control performance requirement, all make this two-loop integration a major and difficult issue in the solution of the V/STOL handling qualities problems.

Finally, pilot's being the mixing ground for display and flight control loops means that the pilot develops and operates certain strategies in mixing these "tools" at hand. The NAVTOLAND project efforts include the development of: basic pilot techniques, the micro strategy, in using the information recieved and manipulating the controls; and standardized takeoff and landing procedures, the micro strategy, e.g., flight profiles, operational envelopes, auto/manual decision points, emergency procedures, etc.

The above discussion should make it clear that all NAVTOLAND components, except for the aircraft securing device on the deck, and the efficient integration of them into an operational capability contribute toward improving the handling qualities of the V/STOL in terminal operations. In the paragraphs to follow, the NAVTOLAND project is discussed in terms of products to be anticipated, current project status or state of the art of particular elements and needed developmental efforts, with particular emphasis in handling qualities perspective. Detailed descriptions of the project beyond this paper are found in the NAVTOLAND Program Plan [8]

PRODUCTS OF THE NAVTOLAND PROJECT

It is often somewhat difficult to define the final products of a system integration project like NAVTOLAND. The nearest expression might be that it will be a NAVTOLAND capability package which is a feasibility-demonstrated set of various systems and techniques manifested in design guidelines, specifications, operating manuals software programs and prototype hardwares. The reason for these project component product being basic or generic in nature is that the scopes of coverage and degrees of performance of these components are to be flexibly traded off among them to allow for differences in specific aircraft designs, cost implications, etc., yet to achieve the total capability level that is reasonably standard throughout the Navy and Marine Corps operations. Thus, the design and development of specific V/STOL aircrafts and V/STOL operating ships, in accordance with various applicable specification, are the responsibilities of respective project managers and associated industry; the NAVTOLAND project supports these systems developments by having done a centralized "homework" for incorporating vertical takeoff and landing operational capability.

V/STOL AIRCRAFT T.O. & LANDING DESIGN PARAMETERS

The aircraft design considerations with respect to stability and control requirements as augmented by flight control and pilot's response to display will be addressed by delineating the spectrum of operational situations with known control problem areas such as air turbulence and general wind-over-the deck effect, aircraft motion induced effect such as the side force problems and various thrust variation effects in the ground proximity. The pilot's field of view criteria will be addressed in terms of what the pilot must see from his cockpit perspective, along with requirements imposed by flight profiles and other aircraft maneuvering procedures. What the pilot must see will be delineated in terms of visual cues for performance of specific sub-tasks.

That the current V/STOL handling qualities specifications and informations such as MIL-F-83300, AGARD Report 577 and MIL-H-8501A need refinement and revision is attested by the calling of this workshop and concerned "out cries" elsewhere.[9] The consensus of the concerned is pointed toward making the handling qualities "technology" operational. That is, of course, to say, handling qualities as an aircraft design guideline must be considered in the reality of complex interaction of many factors as discussed by Lamar and Neighbor. Pre-occupation with the mechanical stability and control characteristics and single-channel solution of problems by stability augmentation devices must yield to seeking efficient solutions in and tradeoffs with other pilot aid systems within and external to the aircraft. When Harrier pilots held a workshop on flying qualities and performance in the AV-8 safety symposium, the display and engine thrust were major topics along with the stability and reaction control problems.[9]

Various aspects of V/STOL operations impose special problems in regard to aircraft control characteristics. For example, the hover and landing operation relies heavily on the pilot's visual reference to his surroundings and on precise positioning of the aircraft in all three axis. This situation suggests that special attention be given to pilot's field of view and display augmentation thereof and simultaneously to aircraft translational characteristics. The VAK-191B flight research indicated a high sensitivity of the type and response characteristics of the flight control system to the manner in which the pilot conducts flight tasks in VMC vs IMC and also in different segments of the approach and landing. A test pilot preferred the highly stability-augmented VAK-191B in IMC approach but preferred the force-feel augmented AV-8 in VMC landing maneuver. The height control in V/STOL mode is a function of thrust generated by the propulsive system. Therefore, the propulsive system becomes an inherent part of the flight control system in V/STOL operation. The required thrust to weight ratio and thrust response characteristics to meet all terminal operation situation must be spelled out for the aircraft designers.

The results of various on-going flight research programs, such as NASA Ames' VSTOLAND, NASA Langley's VALT, Navy's X-22A and RAE's Harrier

T MK 2 must be centrally culled out to provide all perspectives data. In addition, specific V/STOL aircraft improvement and development programs such as AV-8A operational improvement, AV-8B, XFV-12A, XV-15 and Navy Type A V/STOL development are and will be yielding information which must be generalized for use by the whole V/STOL design community. To accomplish these tasks would require an efficient, cross-agencies, cross-disciplines and cross-nations cooperation. The NAVTOLAND project has begun the Navy contribution in this cooperation task. One of the more definitive and practical efforts to be started immediably might be a simulation research which incorporates all the factors and subsystems blocks in figure 7 of this paper with adequate measurement and evaluation methodology for each block, including detailed deleaniation of the beginning TASK block and evalution criteria of the end PERFORMANCE block. It should be noted that such an large scope simulation efforts which are required for the R&D of each major subelement such as the visual landing aid, guidance sensor, ship motion predicting, and even the flight control and display interface analysis.

INTEGRATED FLIGHT CONTROLS AND DISPLAYS

The NAVTOLAND project views the flight controls and displays as two complementary subunits of an integrated pilot aid system in the control of the V/STOL aircraft. This integration concept was first described in AGARD Report 594. Figure 8 shows the postulated pilot workload curve as a function of flight control and display subsystems sophistication scales. Toward the increasing end of both subsystems sophistication, inputs from guidance sensors are added to effect three-dimensional flight, i.e., flight path, control. Through analytical work, simulations and flight tests, the NAVTOLAND project will define the acceptable pilot workload loci of interfacing flight control and display capabilities. As discussed in the preceding section on the aircraft design parameters, different flight control/display interface requirements in VMC and IMC will be accounted. Again, depending upon the aircraft system design selection, cost consideration, etc., an appropriate pair of flight control and display capabilities maybe selected by the specific aircraft designers following the specifications or Air System Requirements (AR's) developed under this project. In addition, the integrated system software, i.e., control laws to program both the flight control and display subsystems and the necessary interface between them will be developed and flight proved with the testbed fixed-wing V/STOL and helicopter in operational environment.

The state of the art in effecting automatic approach, hover and simulated vertical landing was demonstrated by Navy's Hovering Vehicle Versatile Automatic Control (HOVVAC) system installed in a helicopter.[10] The X-22A project has also demonstrated similar capability and this project is continuing. Previously mentioned NASA and UK RAE programs are valuable data sources also. Navy has an analytical effort at present to identify various parameters of the flight control and display sophistications to develop a method of defining the optimum mixture points on figure 8.

As discussed previously AGARD Report 594 recommends 15-point R&D tasks in this subject area, which in substance are common goal of the current NAVTOLAND flight control and display subelement. The specific areas which require further intensive effort are:

1. Continue development of the tradoff relationship between flight control and display capabilities.

2. Determination of the operational configurations of the control/display system in IMC/VMC transition.

3. Integration of thrust and stability augmentation to effect an optimum power management and associated pilot and display roles.

4. Interfacing of highly accurate guidance systems information with the digital flight control and display system.

LOW-SPEED SENSOR

The low-speed sensor, which is not currently available either in the AV-8A of fleet operational helicopters, has become one of the regular topics whenever the V/STOL and helicopter pilots and flight test engineer discuss operational problems. This requirement for detecting airspeed below 40 kt, which is the lowest reliable limit of the currently operational airspeed indicator, has to do with the flight envelope warning. Kolway explains, for example, the UH-1N sideslip limits corresponding to 35 kt sideward speed and reaward speed limit of 30 kt can be safely approached with an adequate low-speed sensor, thereby permitting the pilot to achieve the maximum capabilities of the helicopter in hover and low-speed regime.[11] The recent Harrier pilots' safety symposium also raised the same issue by concluding that the lack of an accurate indication of flight envelope airspeeds, among other things, preclude the realization in IMC of full V/STOL potential achievable in VMC. AGARD Report 594 also recommended sensors with adequate precision in low speed flight regime of the V/STOL. It is interesting to note that Anderson in his review of AGARD Report 577, commenting on XC-142 and P.1127 test results, stated that "in the low airspeed range (85 kt in the P.1127 data cited), the pilot uses attitude as the primary reference."[12]

There are a few low-speed sensors in experimental stage. The accelerated development of such device appears warrented and would contribute toward improved task performance in the handling qualities loop.

ATC. APPROACH AND LANDING GUIDANCE SYSTEMS

The development or structuring of the Air Traffic Control (ATC) or inbound navigation, approach and landing guidance systems and their integration for the V/STOL terminal operations are discussed in detail

in Miyashiro's paper in this workshop and several NAVTOLAND reports including the project program plan.[13] There are, however, some key issues in the V/STOL terminal guidance capability development and some aircraft control and handling qualities related considerations which might deserve discussing in this paper.

It is important to note that currently there exists no operational precision final hover and vertical landing guidance system, say, within 0.2 nautical mile of the touchdown point (see figure 9), as postulated in AGARD Report 594 five years ago. As Miyashiro reported, however, that this capability is about to be prototyped in the NAVTOLAND program. When this capability is achieved, the aircraft control loop can be and must be tightened drastically and the operation moves into a totally new experience in IMC maneuvering flight from the current, very much "seaman's eye" work in VMC. The IMC/VMC transition would occur instant before the touchdown, requiring perhaps more stringent technique of using HUD or of achieving stable aircraft attitudes, etc.

The V/STOL and helicopters can be anticipated to operate within the next decade from some 200 to 300 ships of various types and tactical sites in different surroundings. The approach and landing profiles and procedures may be dictated by these operating conditions. Maximum standardization will be strived in the NAVTOLAND development and installation of the guidance systems for pilot's operational ease and safety. It is important for the guidance system developers to know whether or not and what degrees of steep, curved (both in plan and elevation) or stepped profiles may be needed for various reasons, e.g. minimum fuel, minimum time, maximum descent rate, obstacle/enemy clearance, etc. Of course, these situational variations impose additional requirements to display parameters and to flight control laws, if coupled to guidance signals.

VISUAL LANDING AIDS

The Visual Landing Aids (VLA) include:

1. Dedicated displays or indicators for specific flight guidance parameters such as glide slope, line up, attitude, etc. The well-known "meatball" aircraft carrier optical landing system is an example.

2. Deck markings and lightings to enhance the pilot's perspective of the landing platform, e.g., white flood lighting, deck edge and centerline markings and lights.

3. Various natural cue elements which singularly or collectively give the pilot some secondary position, speed, attitude and other cues, such as grass on the runway, sea surface.

All of these three VLA elements must be organized so that they guide the pilot and do not present an inefficient clutter or not confuse the pilot.

The NAVTOLAND project will define the necessary VLA package configuration which are:

1. Integrated within the total visual scene of the pilot in all of the applicable segments in approach and landing;

2. Useable for each class of ships and tactical sites and respective V/STOL and/or helicopter operations;

3. Standardized across aircraft types, ships and tactical sites as much as possible.

Such VLA packages will consist of:

4. Existing lighting and optical systems validated as parts of the package (existing systems which are found to be inadequate, confusing or non-contributing would be eliminated);

5. Additional lighting schemes and other visual cue enhancement devices;

6. Other optical devices which may be coupled to non-VLA guidance and control sensors such as electronic guidance sensor, aircraft control systems or ship motion sensors.

Figure 10 depicts the general arrangement of the currently operational VLA assortment aboard a typical aviation facility ship. The clutter factor is evident in this piecemeal and quick-patch evolved configuration. It is also an extension of the aircraft carrier VLA "know-how", which naturally emphasized precision in approach for the constant speed and glide slope CTOL flying requirement (drop-line lights line-up aid and glide slope indicator) rather than precision in touchdown which is essential for V/STOL and helicopter's continuously maneuvering flight.

From the standpoint of handling qualities, the following considerations in the V/STOL VLA development are pertinent:

1. The lower weather minima of the project goal require increased VLA performance at visual threshold. For varying operational visual threshold ranges VLA performance requirements for corresponding flying tasks must be met.

2. VLA signals must conform to V/STOL and helicopter peculiar, optimized flight paths.

3. The pilot's field-of-view limitations and precision final landing maneuvering cue requirements demand closer interface with (smoother transition from) and/or direct use of electronic guidance signals in the VLA design.

4. All of the required visual information, i.e. track, height, close-in position and aircraft attitudes, must be provided in total-perspective combination throughout the approach and landing segments.

SHIP MOTION INFORMATION

The ship motion information is required for V/STOL terminal operation in two forms, i.e., real time motion data and motion prediction or forecasting. The real time motion information is required for stablizing various ship-installed guidance signal sources. No new technology development is required for this purpose; existing ship motion data in conjunction with any required additional data which can be obtained through future shipboard trials, tow tank research or computer simulation will adequately meet the project needs. The technique for forecasting of ship motion lull period for pilot aid and guidance system (decision making) coupling is at a primitive stage of development. It is generally agreed that the high pilot workload and flight control system saturation in the V/STOL landing maneuvering flight do not permit the deck-chasing mode of final landing as done in the carrier automatic landing system. Currently, only the pilot can judge for himself when a lull in ship motion will occur and attempt to land during that lull.

Several experimental schemes for ship motion prediction are under study. One concept, an energy index scheme, attempts empirically and mathematically to describe the ship's energy level. The results of this scheme appear to be more periodic and regular than the extremely random ship motions. Limited data obtained during shipboard trials are being examined presently to determine merits of this approach. Another concept is one in which ship motion history is processed in mathematical filters. This approach applied in limited actual data indicated the possibility of forecasting ship motion within a one-cycle time frame of 7 to 10 seconds. Figure 11 shows an example of the computation. Additional computations are being conducted to verify merits of this scheme.

The use of artificially or technologically derived and displayed ship motion information by the pilot as a total information source in complete darkness or adverse weather or as a quantified aid to his "seaman's eye" will be a new experience and will have to be integrated into his handling qualities loop. Probably one of the important tasks to be done is to determine and develop method (location, symbology, dynamics and integration) of displaying such ship motion information to the pilot.

AIRCRAFT SECURING SYSTEM

Some past helicopter shipboard tests and analytical data have postulated that in small aviation facility ships the aircraft could make successful landing in Sea State beyond 3 by the ship-lull judging technique, but it would be extremely difficult to hold the aircraft on the deck in ensuing large ship deck motions. This obviously prompted the LAMPS Project Office development of the helicopter hauldown and rapid securing system as shown in figure 12. The NAVTOLAND project will monitor this effort while studying shipboard securing requirement for the V/STOL aircraft vis-a-vis respective operating ship sizes and motion characteristics. No pilot flying technique would be involved for the V/STOL, obviously. The LAMPS development is expected to develop associated pilot techniques for the helicopter.

AIR WAKE INFORMATION

The air wake and wind-over-the-deck (WOD) are major factors in affecting handling qualities in the close-proximity terminal operation and major operational envelope limiting parameters. Yet, little is known about the characteristics of the air flow in the vicinity of small aviation facility ships. The operational limits and pilot's experience in coping with adverse effects of air wake turbulence are obtained by a process of trial and error. AGARD Report 594 also warned about particular problems for V/STOL aircraft in approach and landing under high cross winds and recommended theoretical and flight investigations in this area to be carried out as soon as possible.

The Navy has initiated a wind tunnel model tests and analysis to develop a mathematical model of the turbulence. A laser doppler remote wind measurement device has been tested aboard a carrier and is currently being proposed for additional tests.

Detailed knowledge of ship air wake is necessary for a complete analysis of V/STOL aircraft control problems especially in simulation research, sea trial test planning and evaluation and (measurement capability for) actual sea trials.

SIMULATION FOR NAVTOLAND DEVELOPMENT

It was suggested earlier in the aircraft design parameters section that an overall handling qualities factors simulation research might be initiated. Such a genral purpose or total system simulation is needed for specific type aircraft development anyway and the NAVTOLAND project can "piggy-back" on it to develop and test the total NAVTOLAND package capability. A number of different kinds of other simulation efforts are needed also to accomplish the development of various NAVTOLAND subelements. These include: mathematical modeling for quantitative, comparative analyses of candidate system concepts through prototype development; fixed base man-in-the-loop simulation for broadbase comparison by pilot's evaluation of competing concepts through prototype development; and moving base, high fidelity man-in the-loop simulation for evaluation and development of prototype

systems and associated pilot techniques and flight procedures. These simulation facilities will be used in support of four functions: (1) Problem analysis and concept evaluation; (2) Prototype hardware development; (3) Flight test; and (4) Pilot techniques/procedures development. An initial look at these NAVTOLAND simulation needs has been described by Fortenbaugh.[14] The project office is in process of formulating detailed plans for the NAVTOLAND simulation programs.

NAVTOLAND PROJECT PLAN

CURRENT STATUS

Figure 13 is an overview of the NAVTOLAND project with the current operational limitations and the project goals at the top. Currently, the Navy effort consists of a number of Exploratory Development programs in various supporting technologies for feasibility investigations. In the Advanced Development which has been submitted for POM-79 budget process, the NAVTOLAND components will be developed, integrated into a total system package, installed in one testbed V/STOL aircraft, one testbed helicopter and a selected aviation facility ship, respectively, and the feasibility of the package, demonstrated in shipboard and tactical site environment.

DEVELOPMENT SCHEDULE

Figure 14 illustrates the "two pronged" approach of the NAVTOLAND capability development to ensure that the capability goal achieved will be a cost-effective, technically logical extension of interim capabilities which the various V/STOL aircraft developmental and operational communities are evolving. The NAVTOLAND project office will monitor and participate in these interim activities by timely inputs of project results as they become available as well as judicious midcourse reorientations to ensure minimum retrofit of existing capabilities.

The NAVTOLAND program schedule with assumed FY 79 Advanced Development start is shown in figure 15. Throughout the program, the milestones planning and adjustment will be coordinated with various Navy aircraft programs.

PROJECT COORDINATION

Figure 16 is presented merely to point up the multi-discipline, multi-authority, multiple-data-source and multiple-customer nature of coordination effort in which the V/STOL terminal operation capability development project like NAVTOLAND must become involved. This may be another reason for the question of "marking time" raised in the beginning of this paper. It is hoped that this paper has

presented some evidence that the Navy is not marking time in the development of V/STOL operational capability from ships and tactical sites. We are marching forward if not running toward the goal.

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NAVTOLAND (NAVY VTOL CAPABILITY DEVELOPMENT)

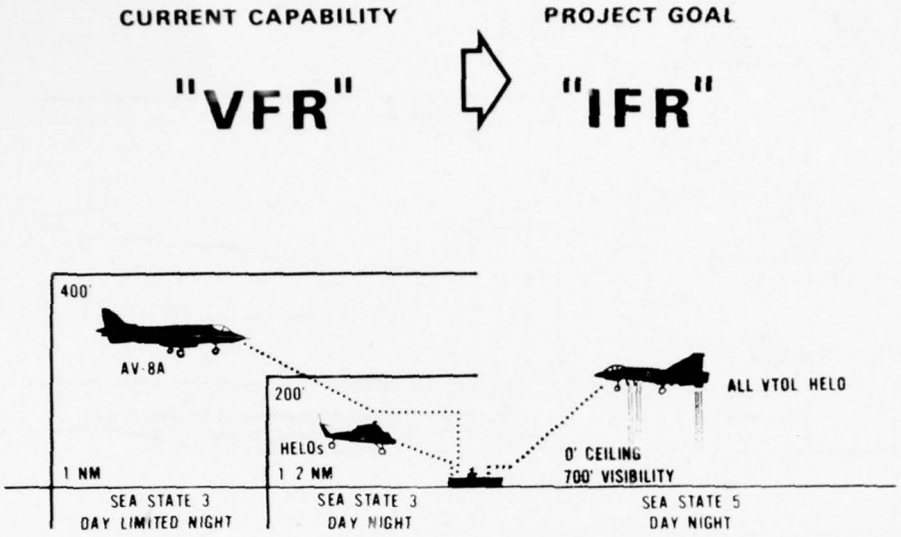


FIGURE 1

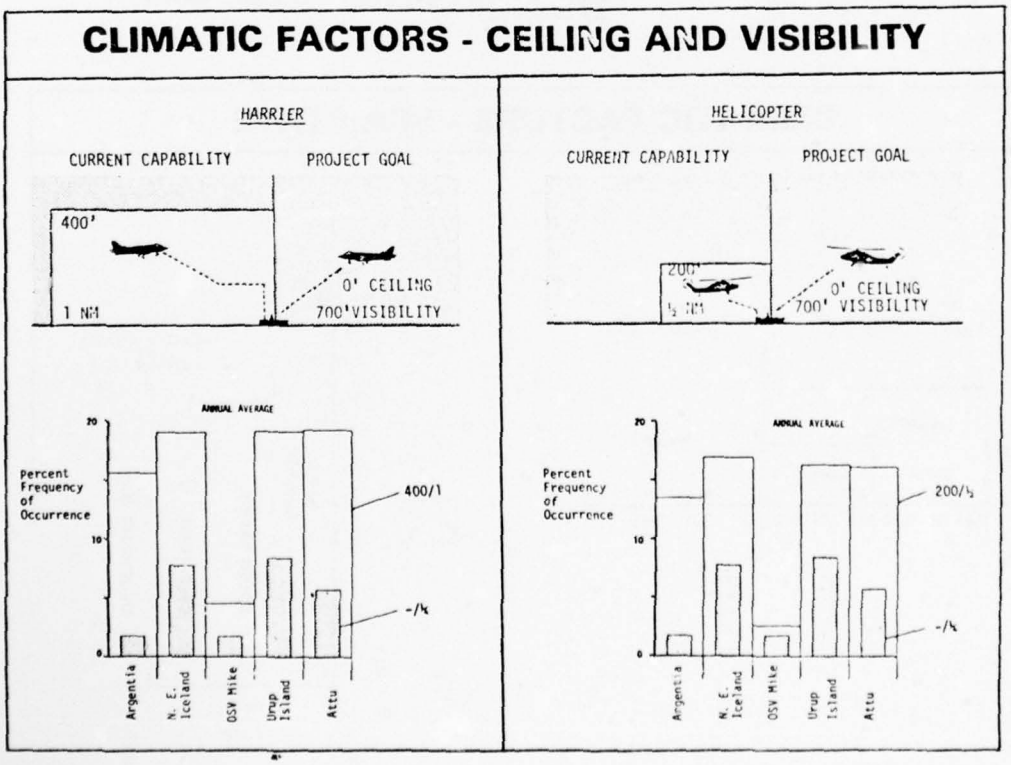


FIGURE 2

CLIMATIC FACTORS - NORTH SEA COASTAL AREA

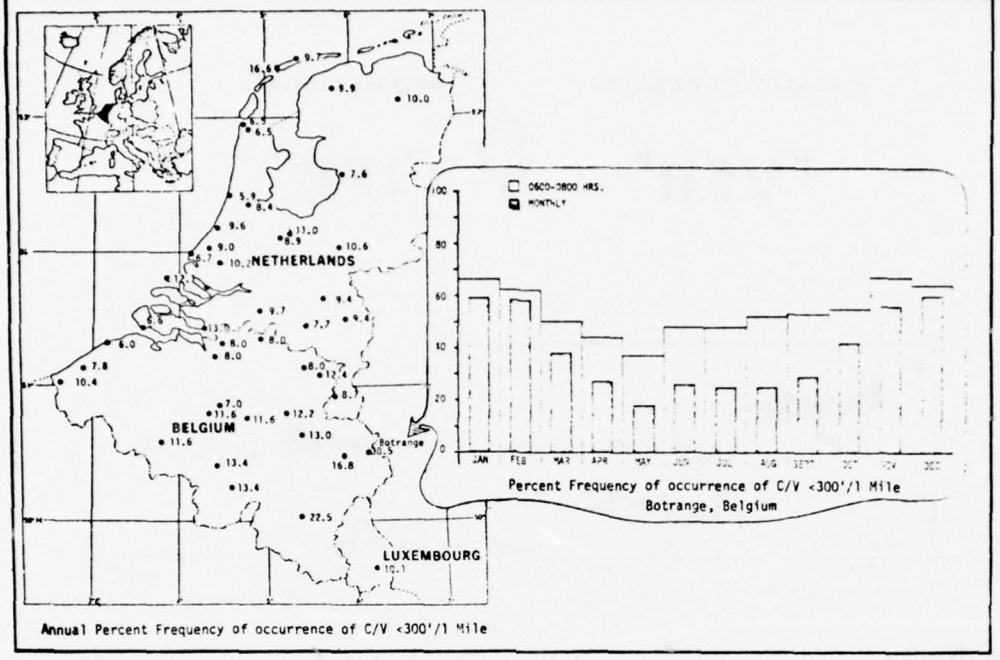


FIGURE 3

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CLIMATIC FACTORS - SEA STATE

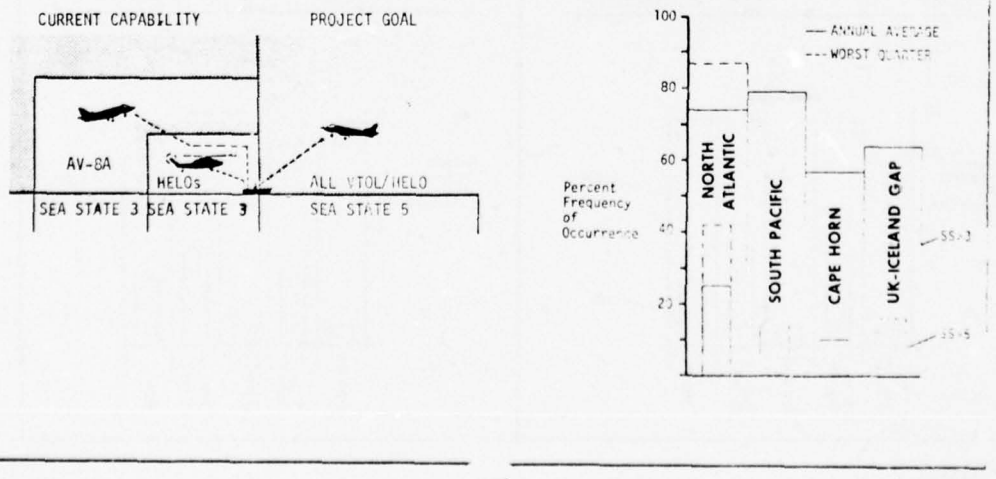


FIGURE 4

NAVTOLAND (NAVY VTOL CAPABILITY DEVELOPMENT)

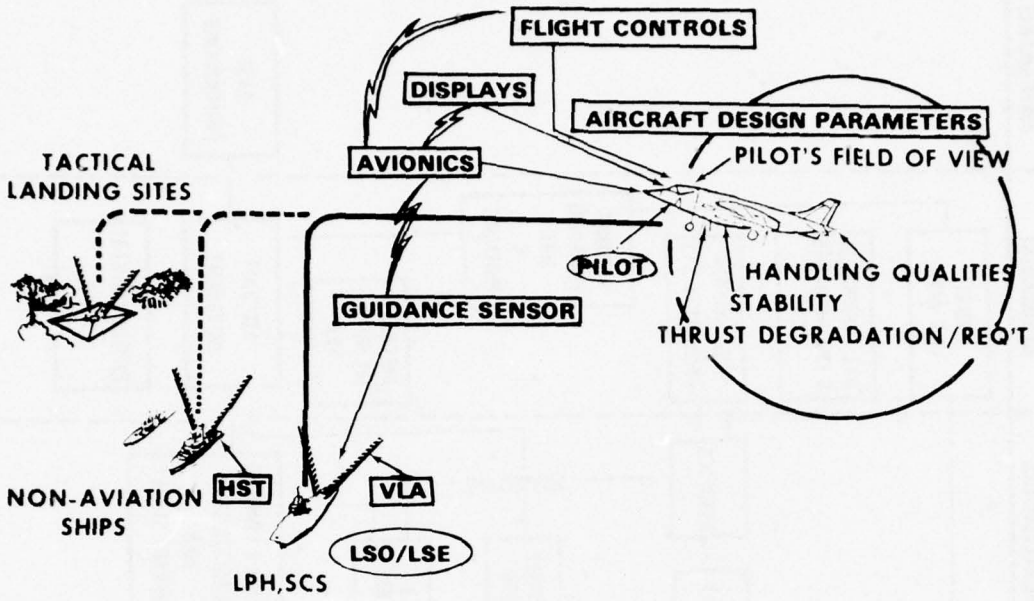


FIGURE 5

HANDLING QUALITIES FACTORS (RE. COOPER & HARPER)

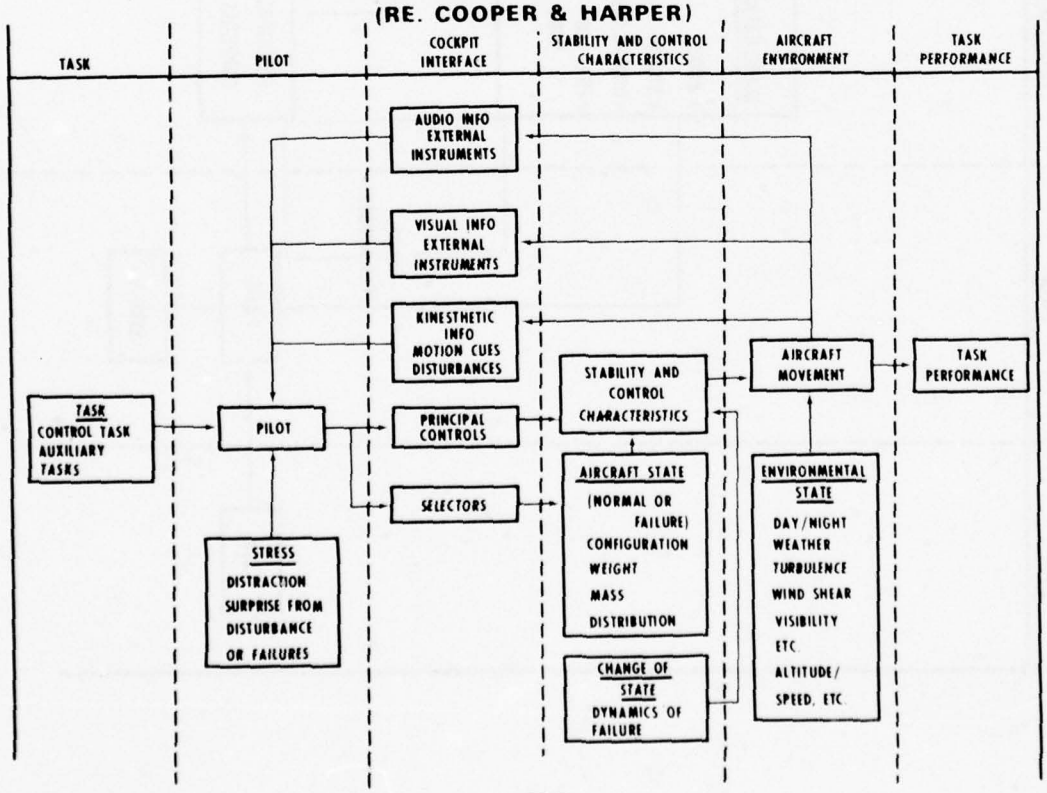


FIGURE 6

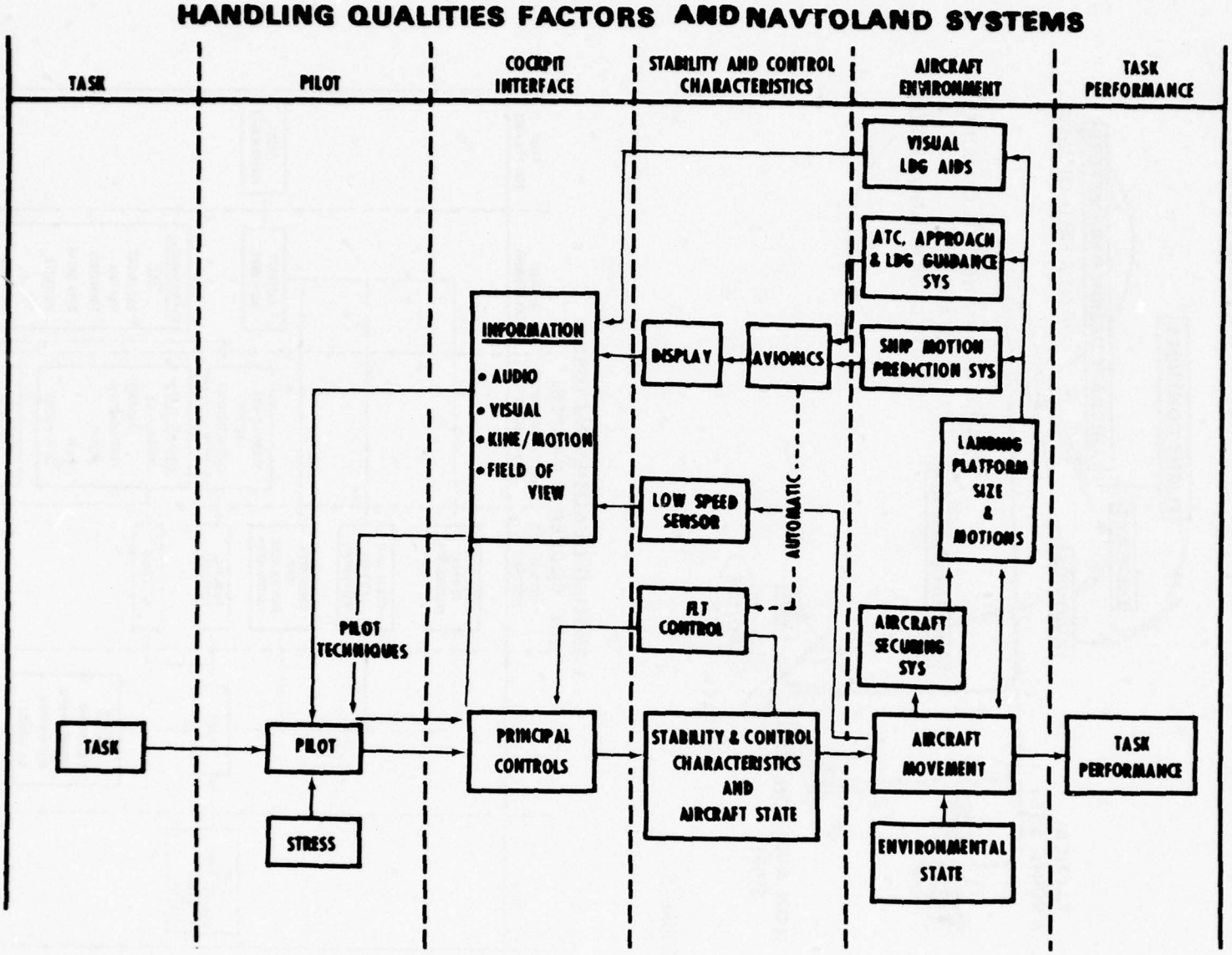

HANDLING QUALITIES FACTORS AND NAVTOLAND SYSTEMS
TASK
PILOT
COCKPIT INTERFACE
STABILITY AND CONTROL CHARACTERISTICS
AIRCRAFT ENVIRONMENT
TASK PERFORMANCE
VISUAL LDG AIDS
ATC, APPROACH & LDG GUIDANCE SYS
INFORMATION
• AUDIO
• VISUAL
• KINE/MOTION
• FIELD OF VIEW
DISPLAY
AVIONICS
SHIP MOTION PREDICTION SYS
LANDING PLATFORM SIZE & MOTIONS
LOW SPEED SENSOR
AUTOMATIC
FLT CONTROL
AIRCRAFT SECURING SYS
PILOT TECHNIQUES
TASK
PILOT
PRINCIPAL CONTROLS
STABILITY & CONTROL CHARACTERISTICS AND AIRCRAFT STATE
AIRCRAFT MOVEMENT
TASK PERFORMANCE
STRESS
ENVIRONMENTAL STATE

FIGURE 7

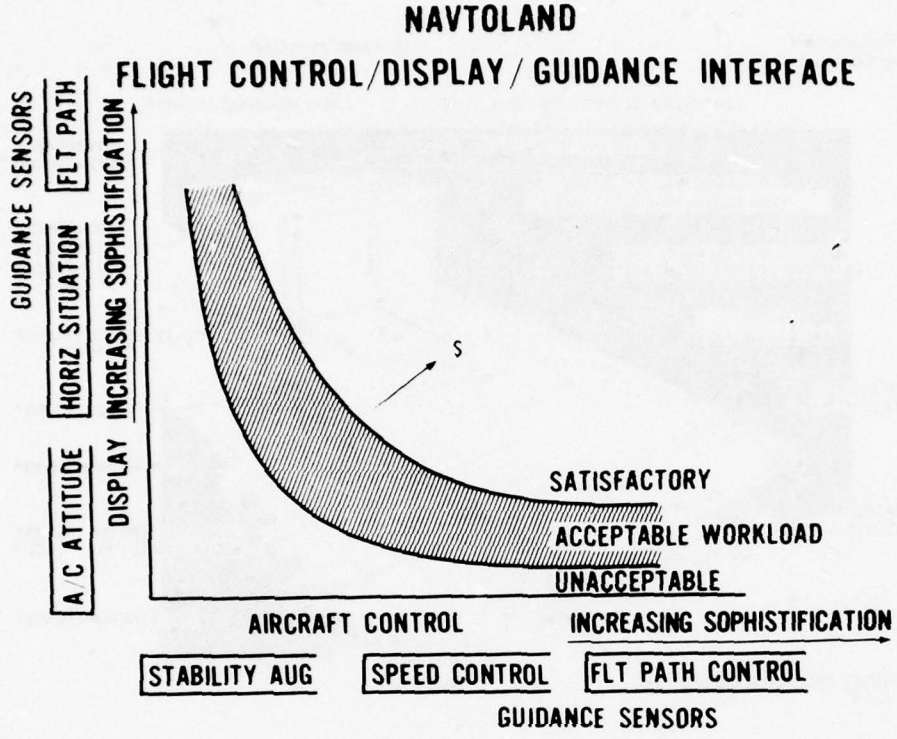


FIGURE 8

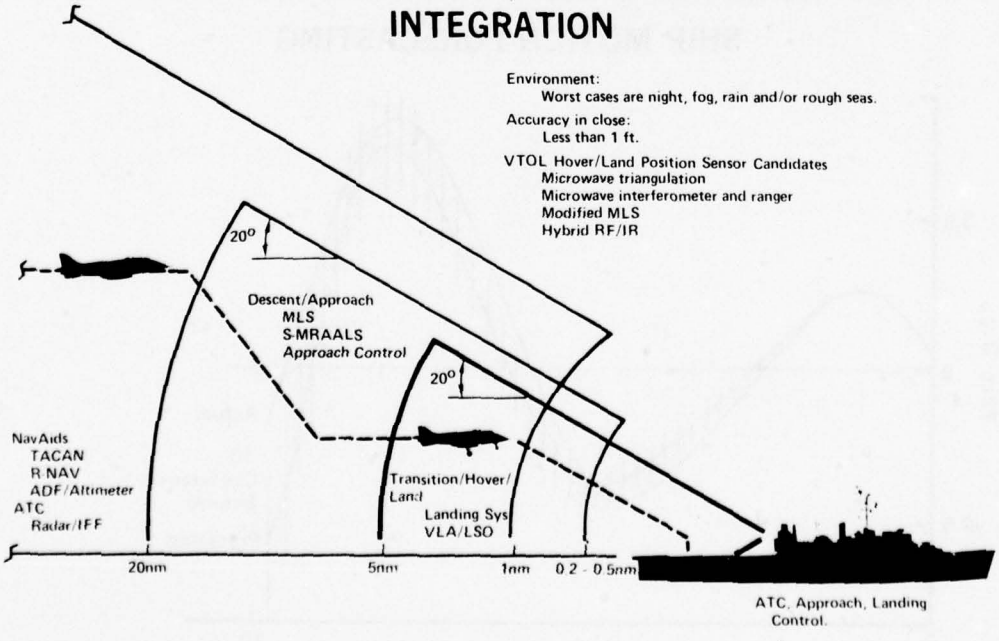
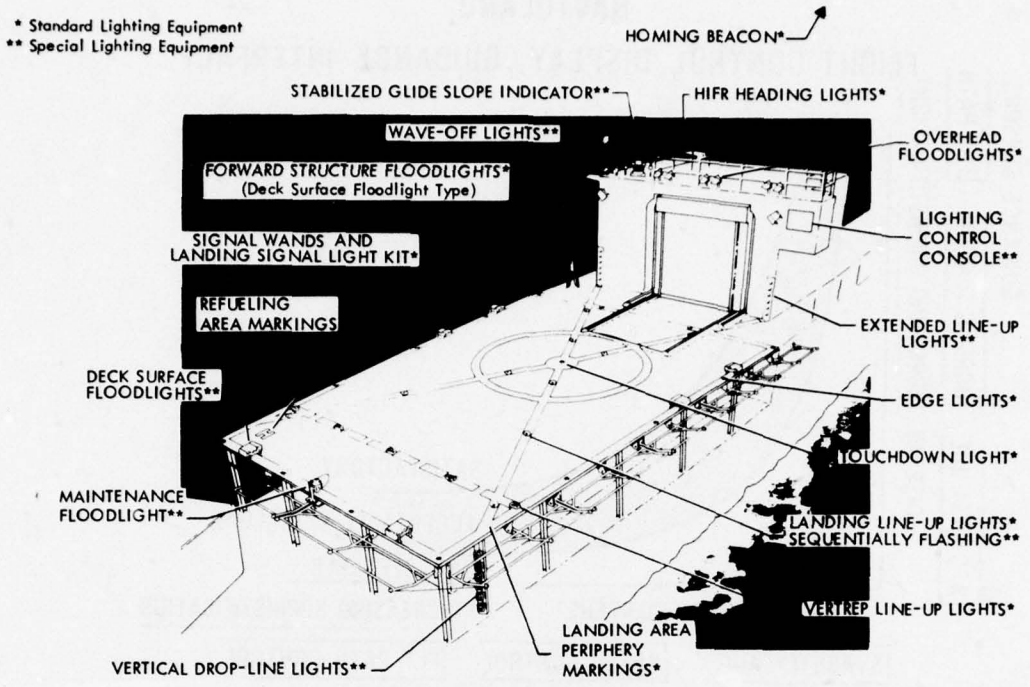


FIGURE 9



Non-Aviation Ship Visual Landing Aids General Arrangement

FIGURE 10

SHIP MOTION FORECASTING

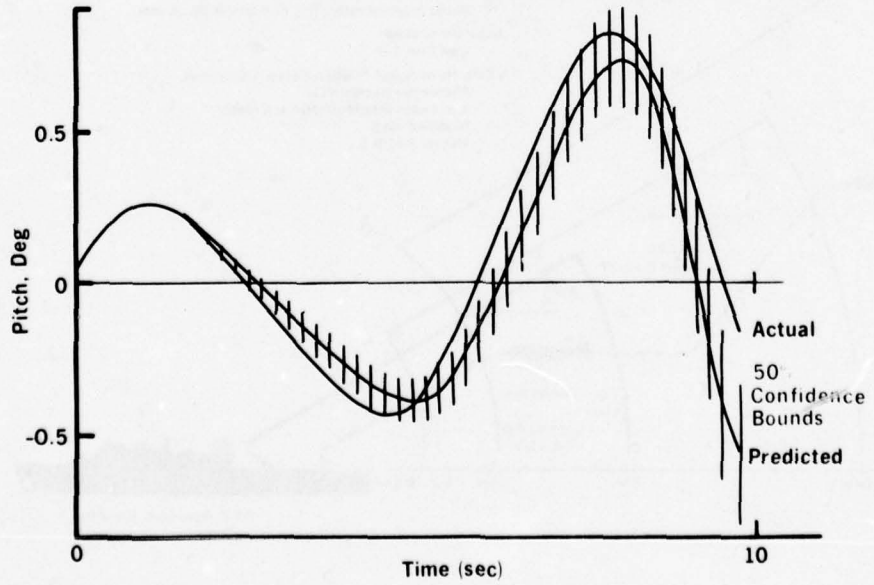


FIGURE 11

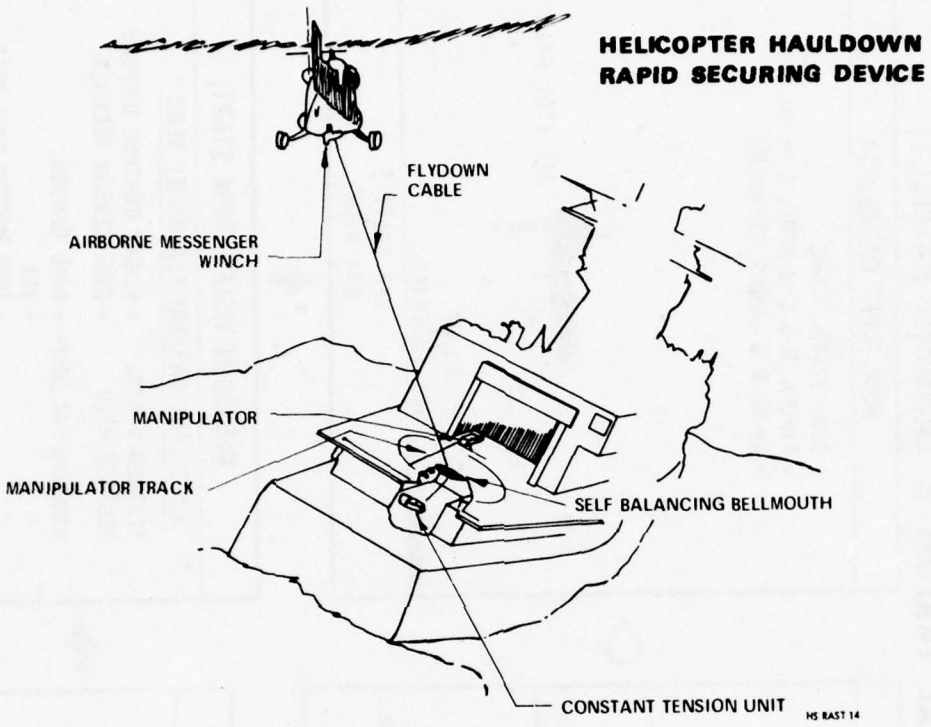
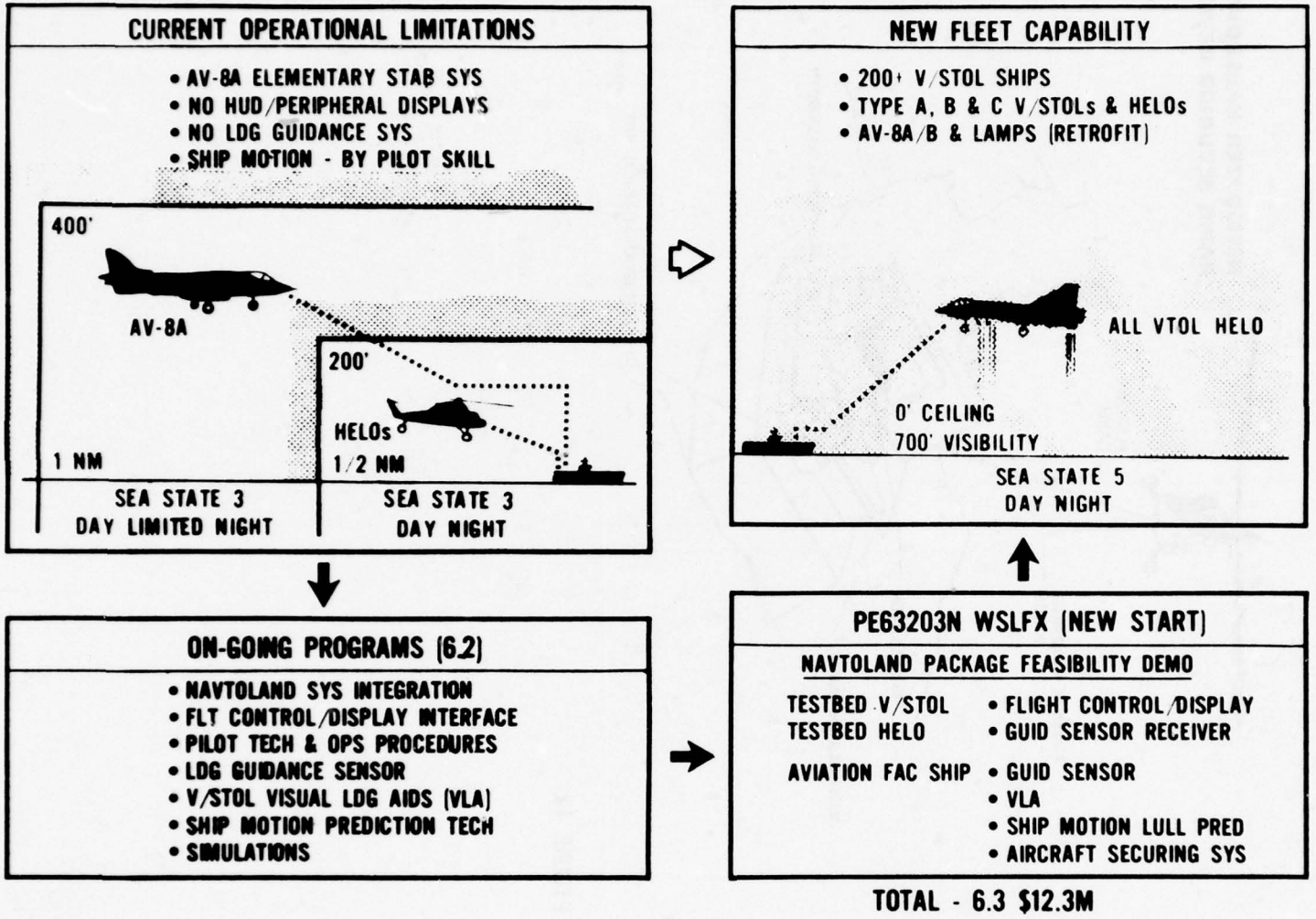

HELICOPTER HAULDOWN
RAPID SECURING DEVICE
FLYDOWN
CABLE
AIRBORNE MESSENGER
WINCH
MANIPULATOR
MANIPULATOR TRACK
SELF BALANCING BELLMOUTH
CONSTANT TENSION UNIT
HS RAST 14

FIGURE 12

P.E. 63203N PROJ. WSLFX

NAVTOLAND (NAVY VERTICAL TAKEOFF & LANDING PROJECT)



TOTAL - 6.3 $12.3M

FIGURE 13

NAVTOLAND METHODOLOGY

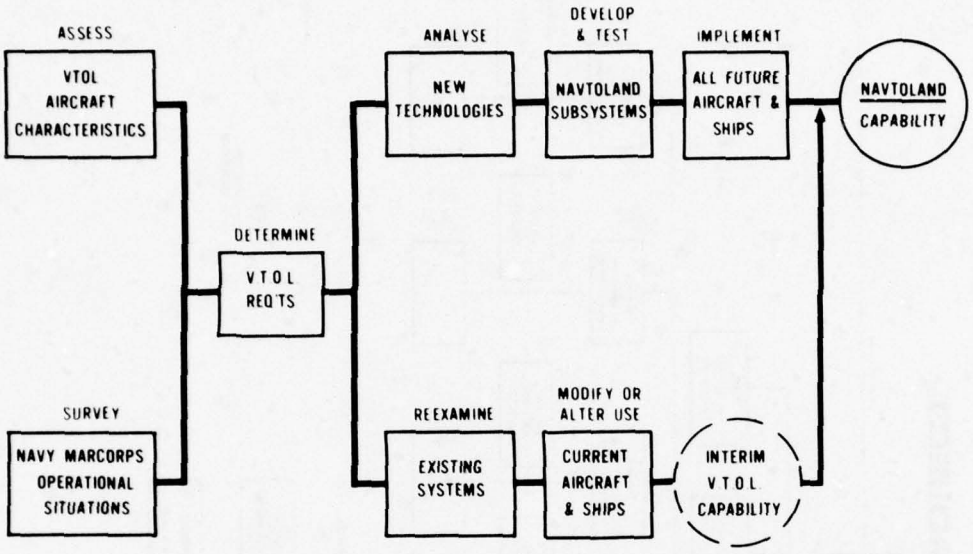


FIGURE 14

NAVTOLAND DEVELOPMENT SCHEDULE

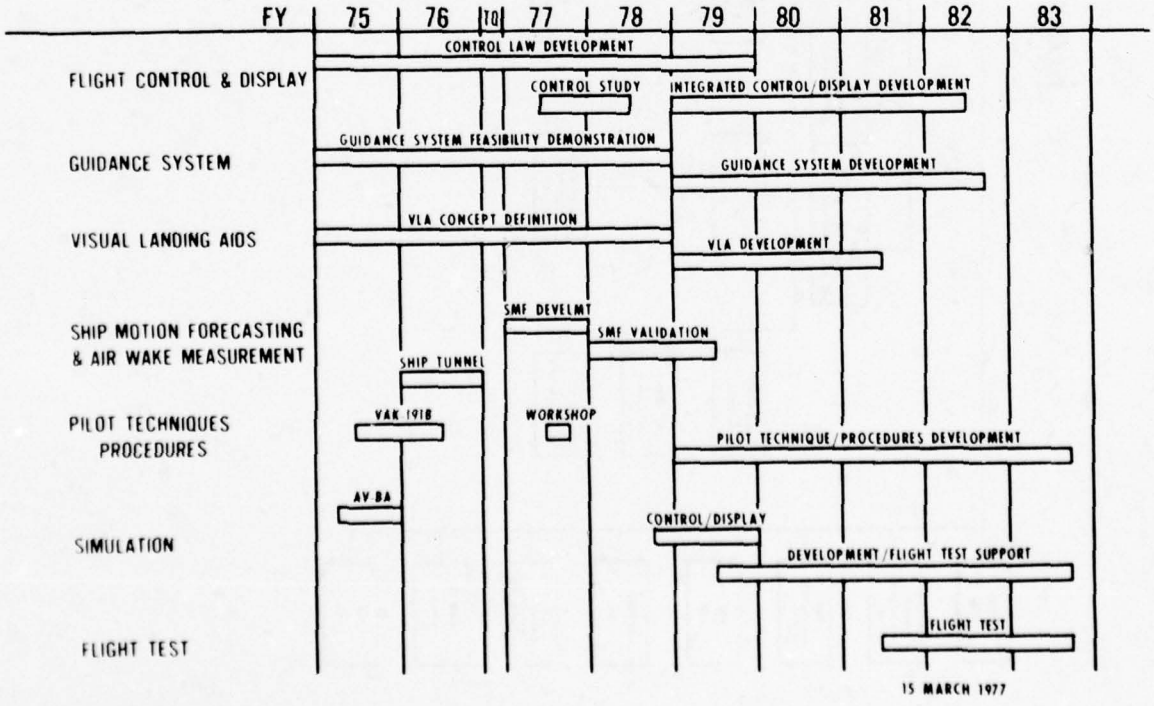


FIGURE 15

NAVTOLAND PROJECT

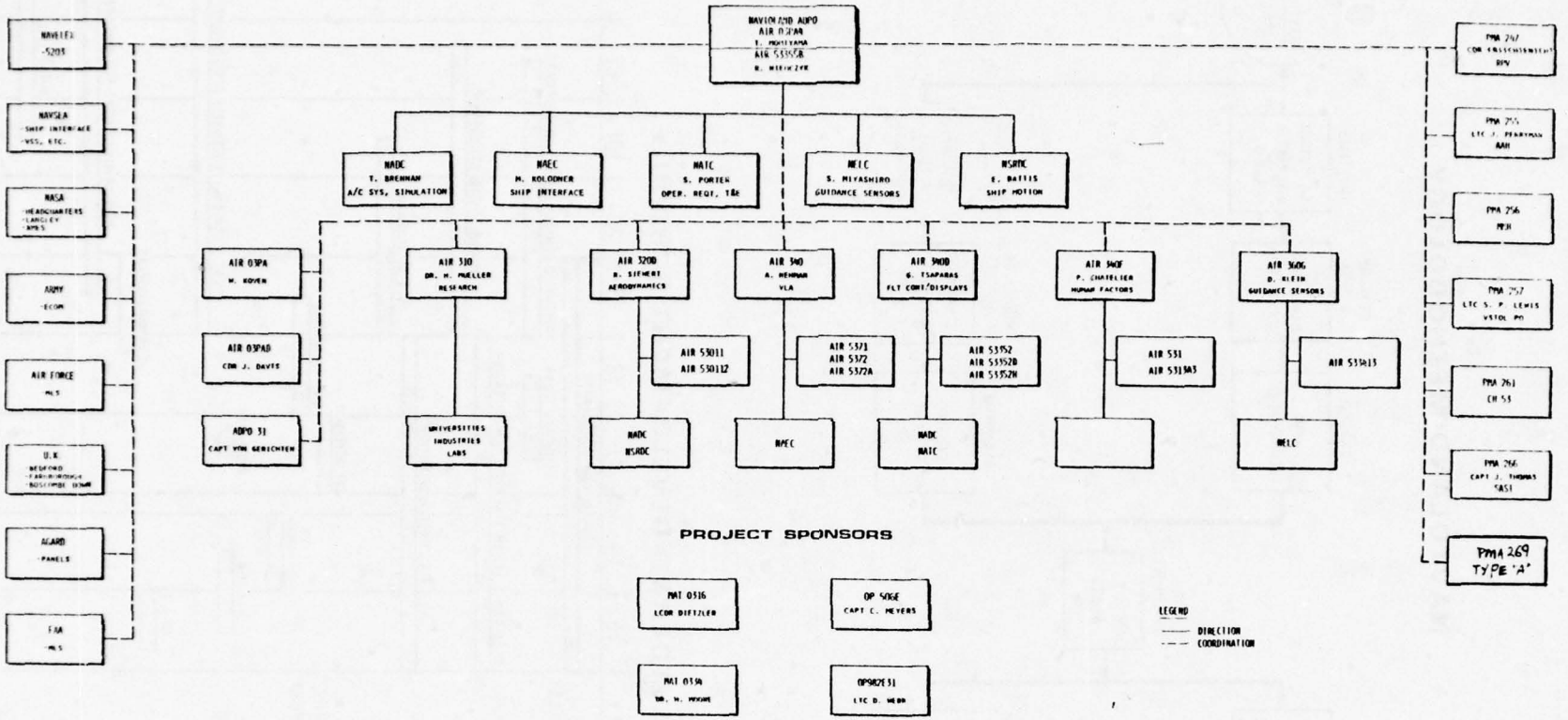


FIGURE 16

DISCUSSION

CDR Olson: I have one comment to make. Specifying a ceiling and visibility (0/700) in sea state five is very misleading. Sea state five doesn't tell the pilot anything about what really concerns him; namely, the ship motion. It's the motion of the platform that counts, not the sea state and not the waves.

Tom Momiyama: O.K., let me comment on that by stating that you're quite correct. We (at NAVAIR) don't like the term "sea state" either. However, if you are talking about taking care of two to three hundred ships and all the associated helicopters and V/STOL's, the 0/700 goal in a sea state five condition does make sense. At present, shipboard operating limits are based upon angles such as pitch and roll, and there are potentially 70 classes of ships to be specified. Making this type of detailed definition in a presentation such as this one would have complicated the situation and made the charts considerably busy. Therefore, I chose to use a sea state approach for making definitions in a concise manner. We are aware of your concern, and we do agree with you.

WORKSHOP PANEL FORUMS

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NAVY/NASA V/STOL FLYING QUALITIES WORKSHOP

VSTOL Flying Qualities Requirements

Dale Hutchins

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I. INTORDUCTION

We attempted, in our panel workshop, to identify a number of gaps in the data base, where the Navy might better plan and program some of its follow-on research efforts.

II. OVERVIEW

We also discussed different aspects of the criteria that make up the specification which seem to be causing problems for some of the aircraft designers.

1. Specify the wind and directional requirements based upon operational requirements for maneuvers, STO

2. Identify control power requirements in terms of operation mission maneuvers
   a. Include displacements (lateral, fore and aft) as well as attitudes.
   b. Include ship environment (turbulence, wind, motion)

3. Specify vertical control requirements in terms of:
   a. Thrust margin, T/W, vertical response
   b. During mission maneuvers with turbulence and wind environment

4. Identify criteria for critical combinations of control
   a. Simultaneous control applications
   b. Minimum acceptable control for these conditions

5. Criteria for IGE Control requirements
   a. Identify criteria for IGE control requirements if operationally required
   b. Specify some criteria such as "NO LOSS OF CONTROL IGE" or "MINIMUM TIME TO/FROM SOME ALTITUDE OR HEIGHT"

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6. Ability to hold trim
   a. Stability about trim for VTO/VL operations
   b. Allow pilots to address other tasks without attention to trim

7. Identify hovering precision task
   a. Spot hover or station keeping
   b. Moving ship

8. Define transition/conversion requirements
   a. Flight path control
   b. Specify mission requirements for flight paths
   c. Identify transition corridor

9. Identify requirements for different:
   a. Classes/sizes of aircraft
   b. flight phases
   c. IFR/VFR
   d. Automatic modes

10. Expand data base for:
   a. Ship motions
   b. Turbulence/gust criteria
   c. Sidearm controllers (mechanical characteristics)
   d. Minimum acceptable control for failures and degradations
   e. Control requirements for unstable aircraft

III. PANEL COMMENTS

1. (Slide no. 1) One of the things that gave everybody a lot of problems when designing the control system, the control power, and the complete airplane, was the 35 knot wind from any direction that is in 83300. I think that we in the Navy feel that the 35 knots is pretty close to an operational requirement, but what we really need to do is to specify the wind and the direction based upon operational requirements. It should be justified better than is the present situation in 83300. We should identify the VTOL maneuvers including the short takeoff case also when trying to specify the required wind velocities and directions for launch and recovery operations.

2. (Slide no. 2) Another major problem was trying to identify control power requirements in terms of "Real-World" operational missions. Right now, the specs seem to place most of its emphasis on control power in terms of attitude changes. We really need to consider and define some requirements in terms of displacements as well as attitudes. The Harrier, in current operations will frequently come up and establish a hover at the side of the ship, and then slide in sideways and down. Helicopter people do the same thing. There is a need to define those kind of maneuvers and identify the displacement control power that goes with them. And those control powers should be specified in the "Real-World" ship environment including the turbulence and the winds that go along with that ship motion.

3. (Slide no. 3) In my opinion, a lot of confusion exists over what the vertical control requirements are. Right now, the specification just identifies them in terms of thrust-to-weight ratio or an incremental "g". It doesn't indicate whether that's to be in a calm, clear air..or what. People felt that the Navy could do a better jot of establishing criteria for thrust margins, thrust-to-weight ratio itself and the vertical response characteristics that we're hoping to obtain from an airplane during its mission maneuvers; i.e., vertical takeoff, vertical landing in the turbulence and wind environment. Also, these three items should be identified in conjunction with other demands on the control power such as attitude or displacement requirements. If the "Real-World" mission were to establish a hover off the side of a ship, then slide-in and start down..or if it were a vertical takeoff from a small ship with turning at the same time to final fly-away heading, then that should be defined.

4. (Slide no. 4) A lot of people feel that we need to be more specific, more definitive on the requirements for critical combinations of control than is presently stated in the specs. We feel that a better definition is needed and perhaps we should attempt to identify a minimal acceptable control in this case rather than just specifying a single number for each attitude as we have previously. Maybe we could specify something in terns of roll and pitch without a yaw input. Or if we really want all three combinations together, then the identification might be better by relating it with a mission requirement.

5. (Slide no. 5) O.K., the other one is the ground effects. If we expect any of these airplanes to operate in ground effect, then we really need to specify the criteria for the operational requirements. Otherwise, as in the case of the Harrier, we try to avoid it. And if that's going to be the case with other VTOL airplanes, then we might be better off...we would probably be better off...specifying some other motherhood statements like these (pointing to the vuegraph).

6. (Slide no. 6) O.K., another point was our trim requirement. In conjunction with the trim requirement, what do we really mean? Are we talking about the ability for the airplane to hold trim, the stability around trim and trying to reduce the pilot workload? What kind of trim stability do we really want so that the pilot, once he does establish trim, can ignore the trim situation and devote his attention to other task requirements.

7. (Slide no. 7) O.K., there's a good bit of discussion about the need to dientify and specify the hovering precision task requirement. Other than just say "free-air hover, 35 knots of wind from any direction". In the shipboard problem...what we're really doing is talking about a precision spot hover, either over the ship or station keeping with the ship.

8. (Slide no. 8) O.K., right now the specs put a lot of emphasis on fixed point operation in the transition conversion regime. A lot

VSTOL airplanes won't spend a lot of time in there, like the Harrier doesn't now. It's a problem to be overcome as quickly as possible. And the thought was that we should specify requirements in terms of flight path control and try to identify a transition corridor. Let the designer work on that aspect of it and decide for himself how best to get through that transition corridor. In conjunction with this, we spent a bit of time trying to discuss whether or not there ought to be a control requirement or a specification requirement on the number of controllers that the pilot had to manipulate. I think that in the final analysis, we concluded that that ought to be a designer initiative.

9. (Slide no. 9) O.K., then there's some requirements for identifying the requirements for VSTOL airplanes in terms of the different classes and sizes of airplanes, the different flight phases..where they are different for different airplanes, let us identify them.. The same for IFR/VFR operations and also the automatic modes of operation.

10. (Slide no. 10) O.K., and finally, this is a list of the gaps as we saw them. Very definitely, we need to expand the data base and define a turbulence-gust criteria that people can use so that they can start doing control system sizing studies, and flight simulation studies. We need to define the kinds of ship motions that we are talking about. As LCDR Steve Olson from the CNA said yesterday, don't just give motions or sea-state conditions for God's sake, tie it down in terms of probabilities. If we're going to operate on a 15 degree rolling deck, he wants to know it it's a 1:10 or a 1:1000 operation, or whatever. O.K., the next one...there is very little understood about mechanical characteristics and requirements on control harmony, forces, gradients and all the side arm controllers. Right now, the specs don't identify or treat that at all.

Also people are looking for guidance in terms of the minimum acceptable control that we can accept for failure cases, control degradation. And then finally, the control requirements for unstable aircraft...Whether these control requirements should be more demanding.

DISCUSSION

Bob Woodcock: This summary was put together very well. However, we were asked to provide some priorities, and I don't think that it was possible to do that in your list. For example, at the very bottom of the list was "control requirements for failure cases in presence of degradations", and this may well be the thing that designs an important part of the airplane. We need to say that the priorities are not necessarily in the order of the overview.

Dale Hutchins: Yes, I agree. I don't know what we are going to do about the priorities. Since this listing from the workshop will be disseminated to all the people here at the meeting, it will be sometime in the future before we come to grips with that and establish the priorities. Certainly Mr. Siewert and others responsible for funding the research programs are going to need it.

NAVY/NASA V/STOL FLYING QUALITIES WORKSHOP

Seaborne Launch and Recovery

Richard Niemczyk

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I. INTRODUCTION

Our subcommittee had a very lively discussion on the subject of Sea borne Launch and Recovery. I am uncertain whether we reached a consensus, but Russ Hendrick (who was the co-chairman) and myself have summarized what we considered to be the group's main concerns in this area and that is what I'll now present.

II. OVERVIEW

What we tried to do was come up with a logical flow of how things should be done, and we divided our comments up into two categories:

a. basic technology

b. application studies

III. PANEL COMMENTS

a. BASIC TECHNOLOGY

In the basic technology area, the things that we think need to be done first in order to have some impact upon the Type A design studies that are ongoing are shown on the first slide (VG #1).

1. Our number one priority is the dynamic math model of a ship. As we learned yesterday, the motion information for a ship is available. The other one, of course, is the turbulence around the ship. And we feel that the first thing that we need to get going, if we are going to make an operational VSTOL Type A airplane (or any other kind of VSTOL) is to get that ship-generated turbulence mode. We strongly recommend that something be done about getting a turbulence model started for the DD-963 class of destroyers, since this is the smallest size ship that the Type A is supposed to operate

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from. That's basic technology, which is necessary, not only for Type A, but for all VSTOL aircraft.

2. The next one is in the area of the landing position sensor. We need to keep that area going, because if we are going to be operating in minimums we need some sort of loading position sensor. I'll talk more about this a little later.

3. The last one is "enhanced vehicle control qualities". We know we're going to have an unstable aircraft in hover; we're already putting a stability augmentation system on the aircraft to stabilize it in the hover mode, or transition, and in the jet-borne lift area. Let's keep looking at enhancing the control qualities in that area such as the velocity stabilization systems which we talked about earlier. Looking at other ideas that are going to make the airplane a better flying, better controlled airplane for the pilot, not just something that he can live with, but something that can enhance his capability to complete his mission.

b. APPLICATION STUDIES

VG #2 Based upon the idea that we've got these basic technology ideas out of the way, then we start looking at how we are going to apply these. In this list is an orderly flow of ideas that need to be done. They're things that we feel must occur in order to correctly identify the environment the VSTOL is going to operate in.

1. First of all, there is an operational scenario study.. How many ships are we going to be operating off of .. How many aircraft are we going to have on these ships .. What's the mix of all these things .. How are we going to deploy these ships and these aircraft .. What's our operational requirement...things of this nature. These are the things that right now, as far as we can tell, are completely open. And somebody, somewhere has to do something in order to map out this strategy and tell it to us so that we can start getting busy with the design of the aircraft. We include EMCON in there as a specific issue because of the impact that that has upon the use of radars for guiding the aircraft back to the ship, the guidance and electronic systems on the ship itself, and what we're going to have to do to bring this aircraft back onboard the mother ship.

2. The next area is the ship-aircraft capability mix. This is by example...if we are buying one ship and a 1000 airplanes... maybe we can afford to put a lot of capability on the ship such as visual landing aids and guidance systems, and then make a "very smart ship-dumb airplane" so to speak. On the other hand, if we're going to have one airplane and 1000 ships, then we want the "dumb ship-smart airplane" concept. This is something, we feel, that will come out of this operational

scenario study. That's why I show this simple example of VLA/Guidance Sensors on the ship vs. perhaps visual enhancement of something such as a FLIR or something on the aircraft that will make it totally independent of the ship environment.

3. The next one was landing position sensors. And this is going to come out of the previous study because if we are in fact going to go to a very stringent use of a guidance system..or what have you, then we're going to need something in this area. We need to define the ceiling, visibility limitations of the system, and the angular coverage for the system. We went through a bit yesterday about this when talking about the NAVTOLAND program, and the goals we've established in there. Those goals were established by NAVTOLAND, nobody else in the Navy did it except us. We feel that we have the rationale for it as we went through yesterday. But is that a true rationale? That is some of the things that'll fall out of this study, we feel.

4. And then, we do a failure strategy. Now here we are looking at what kind of losses can we sustain to the equipment, both ship equipment, air equipment, and still keep the vehicle capable of fulfilling its mission. This is where we feel that we will come up with an operational capability for the aircraft. What loss rates can we sustain?,..what are the degraded modes of operation, and things of this nature. At this point, we take this number (whatever it is) and factor it back up into the top and see how it plays through again. This may be an iterative process arriving at the solution. But I think it is a logical way to come up with what is the operational capability of the aircraft.

c. AIRCRAFT CHARACTERISTICS

(Slide no. 3) Now we come into the subject which is the purpose of the workshop. What are the aircraft characteristics that we need?

1. In the flying qualities area, SAS on, SAS off, good displays, no displays...

2. The control power requirements...

3. The visual information requirements, VLA, the external cues to the pilot...

4. Guidance sensors...These are the meat of the design concepts for the VSTOL aircraft. This is where we need to progress.

(Slide no. 4)...Now on this last slide. I had hoped that I would be last because I wanted this to be the last one that we showed today, but it was the famous boomerang, or whatever it is. We looked at the effects of increasing ship motion and turbulence. You can see in this lower left area

we can land with a degraded system. In the center of the figure we need a full capability system and in the upper right, we are going to the beach. What we need to define is where the two curve limits fall and then maybe we'll have an operational VSTOL.

Any comments from the Committee...any questions?

DISCUSSION

Erich Baitis: We were talking about the wind-turbulence model. We ought to take that through a little bit further. We shouldn't just have wind velocity defined, but we should take it to the airplane and state mean values and orders of magnitude of force upon the airframe.

Niemczyk: That was the intent during the operational study. We would be collecting that sort of information in the analysis. Because of the importance of this information, we recommend that it be done first.

Anon: During the panel discussion, we brought up the question as to what was the relation between the vehicle flying qualities and the amount of landing aids that you need on the ship. I think that is what you meant in the summary chart.

Niemczyk: That's what I was addressing. It's going to be a mix of how much you need and how much you put where.

Louis Schmidt: I would like to make a comment on the ship-generated turbulence model that Erich Baitis raised a point about. Bob Woodcock and I were discussing this subject at lunch and came to the conclusion that, just like in conventional aircraft response dynamics, what is needed is a spectral distribution, RMS levels in various directions a scale of turbulence, and maybe a boundary layer velocity profile vs. distance above the sea. These items would be a logical outgrowth if one were to develop a universal model.

NAVY/NASA V/STOL FLYING QUALITIES WORKSHOP

Flight Controls and Displays Workshop Panel Report

Ronald A. Hess

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I. INTRODUCTION

This workshop panel report contains two main sections entitled respectively, "Overview" and "Panel Comments". The Overview section is somewhat tutorial and is intended to provide a frame of reference for the explicit panel comments in the last section. This list of comments is not exhaustive but rather is indicative of my impression of the major concerns of the panel members in the area of V/STOL flight controls and displays. A list of the panel members and their affiliations is provided after the panel comments.

II. OVERVIEW

The end objective of V/STOL flight control and display requirements is a concrete definition of what an "effective vehicle" should be in order that a given task can be performed with acceptable levels of pilot workload. Effective vehicle includes the basic airframe, the stability and control augmentation system and the display system. In the simplest terms, task performance is quantified by the probability of the pilot/vehicle system safely accomplishing the given task in an operationally representative environment. Pilot workload can be defined in a very general sense as the integrated physical and mental effort required to perform a specified piloting task.

When they occur, deficiencies in the V/STOL effective vehicle are usually heralded by two major symptons, often (but not always) occurring together:

a. inadequate pilot/vehicle performance

b. high pilot workload levels

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Serious inadequacies in pilot/vehicle performance can rarely be tolerated since they compromise the utility of the aircraft and are usually accompanied by unacceptable workload levels. High pilot workload levels are, however, often tolerated in V/STOL operations if they are accompanied by acceptable pilot/vehicle performance. The reasons for not attempting to reduce pilot workload levels in this latter case are varied, but often can be traced to two factors:

a. The means for reducing pilot workload may not be readily apparent, i.e., there may exist an inability to systematically determine the combinations of basic airframe characteristics, stability and control augmentation levels, and display systems that are capable of reducing workload.

b. The cost incurred in reducing pilot workload through increased automation or display sophistication (with concomitant reliability problems) may be prohibitive.

Based upon the foregoing, it can be stated that the existence of the human pilot as an active element in the effective vehicle constitutes one of the primary challenges to successful design and utilization of V/STOL aircraft. The explicit consideration of pilot-centered requirements in control/display design is a necessity if the end objective stated above is to be met in a systematic manner.

III. PANEL COMMENTS

The following comments refer to the V/STOL flight controls and displays problem as viewed by the members of the panel. The order of the comments is not intended to reflect their relative importance.

a. <u>VFR-IFR Operations</u>

1. A re-examination and redefinition of visual requirements (in IFR flight) are needed for V/STOL aircraft, especially in recovery operations.

2. Realistic landing minimums (ceiling and runway visual range) for V/STOL recovery operations need to be specified.

b. <u>Mil-Spec</u>

1. The present Military Specification for Piloted V/STOL Airplanes needs to be updated.

2. The conventional and V/STOL Mil-Specs should match on the borders of flight regimes shared by both.

3. The advisability of stating control power requirements in terms of translational velocity response (with specified maximum allowable attitude changes) rather than attitude response should be investigated.

c. Controls and Displays

1. V/STOL controls and displays should be treated as a single discipline, i.e., an integrated approach should be undertaken in specifying this part of the V/STOL effective vehicle.

2. The potential of such control/display devices as multi-axis side-arm controllers, helmet-mounted dislplays and head-up displays needs to be investigated for possible V/STOL applications.

3. A statement of minimum automation requirements for successful V/STOL operation is needed.

4. In side-by-side crew locations, the question of which seat should be occupied by the pilot needs to be answered, i.e., left seat as in conventional aircraft, or right seat as in rotary wing aircraft.

5. Head-up display symbology, including failure warning indicators, needs to be standardized. Display clutter must be avoided.

6. The question of whether cockpit displays should be integrated (one display serving many purposes) or dedicated (three or four dislplays, each serving a single purpose) needs to be answered.

7. V/STOL powerplant reliability is part of control system reliability and should be addressed as such.

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